

Sgoldstino search at the LHC

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Low-scale supersymmetry breaking scenario in which the breaking scale is around TeV has been discussed as a possibility to obtain a large Higgs mass and to moderate the fine tuning problem. A characteristic feature is that the hidden sector would be accessible at colliders in such a scenario. In this paper, we investigate the phenomenology of sgoldstino which is the scalar component of the goldstino superfield. We present partial widths and branching ratios for sgoldstinos decaying to final states involving Higgs bosons and sparticles which have not been discussed in detail so far.

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1. INTRODUCTION

Supersymmetry (SUSY) is an interesting possibility to explain the smallness of the electroweak symmetry breaking scale. In SUSY, the electroweak symmetry breaking scale can be interpreted in terms of soft breaking parameters (and μ parameter) thus SUSY particles are plausible candidates for new particles that can be produced at the LHC.

Phenomenology of the minimal supersymmetric standard model (MSSM) has widely been studied. There are several possibilities of mediation schemes of SUSY breaking, however, only MSSM particles can be accessible by current colliders in many scenarios *. Since the mediation scale is much higher than the electroweak scale, other sectors are decoupled.

On the other hand, considering very low scale mediation and low scale SUSY breaking $\sim \mathcal{O}(1)$ TeV is still possible [1–8]. In this case, couplings with the hidden sector is not strongly suppressed and consequently affects collider phenomenology. For example, it is possible to produce sgoldstino which is the scalar superpartner of goldstino [9–19]. Furthermore, higher dimensional operators in such a scenario can affect the lightest Higgs boson mass [4, 6, 7, 20–29] and its impact on naturalness is discussed in [21, 22, 24, 26, 27, 30].

In this paper, we investigate low-scale SUSY breaking scenario and specifically study the collider phenomenology of sgoldstino. We present the branching ratios of sgoldstino to Higgs boson final states and SUSY particle final states which have not been studied in detail so far. The decay to Higgs bosons is induced, for example, by $(\mu B \mu / F) \phi_x |H_u|^2$ term (for details, see Section 5). Since this term is not proportional to the electroweak vacuum expectation value (VEV), this decay mode can be important. As one can expect from the equivalence theorem, we also show that the branching ratios to the longitudinal mode of weak gauge bosons are similar to that of the Higgs branch in heavy sgoldstino parameter region.†

The remainder of this paper is organized as follows. In the next section, we introduce a simple effective Lagrangian as an example model of low-scale SUSY breaking scenario. We present Higgs-sgoldstino potential and the Higgs-sgoldstino mixing in Section 3 and the Gaugino-Higgsino-Goldstino mass matrix in Section 4. Then, we study sgoldstino production at the LHC and their subsequent decays in Section 5 and Section 6 is devoted to the summary.

* One of the exceptions is the case of gravitino lightest superpartner particle (LSP). For example, in gauge mediation the next-LSP will decay to gravitino before exiting the detector in some region of the parameter space.

† The branching ratios to the longitudinal mode of weak bosons have been studied, for example, in Refs. [15, 18].

2. LAGRANGIAN

We study the phenomenology of sgoldstino in a simple model which includes MSSM superfields and a singlet sgoldstino chiral superfield $X = \phi_X + \sqrt{2}\theta\psi_X + \theta^2 F_X$. The auxiliary component F_X has a non-zero VEV. The fermionic component ψ_X corresponds to goldstino and the scalar component ϕ_X correspond to scalar and pseudo-scalar boson called sgoldstino and pseudo-sgoldstino, respectively. We consider the following simple lagrangian \mathcal{L}_X ,

$$\mathcal{L}_X = \int d\theta^4 \left(1 - \frac{1}{4} \frac{m_X^2}{F^2} X^\dagger X \right) X^\dagger X + \left(\int d\theta^2 F X + h.c. \right), \quad (1)$$

where the non-zero F-term VEV is $\langle F_X \rangle = -F$ and masses of sgoldstino and pseudo-sgoldstino are obtained to be m_X .

In addition to Eq. (1), we consider the following usual MSSM sector in the lagrangian $\mathcal{L} = \mathcal{L}_K + \mathcal{L}_W + \mathcal{L}_X$,

$$\begin{aligned} \mathcal{L}_K &= \int d\theta^4 \left[\left(1 - \frac{m_{\tilde{f}_i}^2}{F^2} X^\dagger X \right) \Phi_i^\dagger e^V \Phi_i + \left(1 - \frac{m_{H_{u,d}}^2}{F^2} X^\dagger X \right) H_{u,d}^\dagger e^V H_{u,d} \right. \\ &\quad \left. + \left\{ - \left(\frac{\mu}{F} X^\dagger + \frac{B_\mu}{F^2} X^\dagger X \right) H_d \cdot H_u + h.c. \right\} \right], \\ \mathcal{L}_W &= \int d\theta^2 \left[\frac{1}{4} \left(1 + \frac{2M_a}{F} X \right) \text{Tr}[W^{a\alpha} W_\alpha^a] + \left(y_e + \frac{A_e}{F} X \right) H_d \cdot L E^c \right. \\ &\quad \left. + \left(y_d + \frac{A_d}{F} X \right) H_d \cdot Q D^c + \left(y_u + \frac{A_u}{F} X \right) H_u \cdot Q U^c \right] + h.c., \quad (2) \end{aligned}$$

where, $\alpha \cdot \beta = \epsilon_{ij} \alpha^i \beta^j$ and $\epsilon_{12} = 1$. For simplicity, we assume all soft SUSY breaking parameters and μ term are real.

General lagrangian for low-scale SUSY breaking scenario consists of many more possible operators as discussed in [17]. However, this simple lagrangian would be adequate to investigate the phenomenology of sgoldstino at colliders. For example, there is no difference when we consider the μ and B_μ terms to originate from $\mathcal{L}_W \supset \mu_w H_d \cdot H_u + (B_{\mu w}/F) X H_d \cdot H_u$ instead of μ and B_μ terms presented in Eq. (2), up to $\mathcal{O}(1/F)$. Although, the term $\mathcal{L}_W \supset (A_X/F) X X H_d \cdot H_u$ can alter the sgoldstino phenomenology if it exists, therefore we assume these are small for simplicity. The full lagrangian up to $\mathcal{O}(1/F^2)$ is presented in Appendix D.

As will be shown in Section 5, sgoldstino decays via $\mathcal{O}(1/F)$ suppressed couplings. In this paper, we investigate the phenomenology at the leading order and neglect $\mathcal{O}(1/F^2)$ and higher order terms[‡]. If m_{soft}^2/F is not small, the expansion does not work, resulting

[‡] Except in the numerical calculation of neutral higgs masses, see Section 3.2 for details.

in higher dimensional operators becoming non-negligible. Thus, for predictability of this effective Lagrangian, we only consider the parameter space in which $m_{\text{soft}} < \sqrt{F}$.

3. HIGGS-SGOLDSTINO POTENTIAL

In this section we start with the presentation of Higgs and sgoldstino potential for this model. Electroweak symmetry breaking causes Higgs-sgoldstino mixing (and pseudo-Higgs - pseudo-sgoldstino mixing). We solve for the minimization conditions and define mass eigenbasis for such scalar fields.

3.1. Potential

The Higgs-sgoldstino potential is provided by D- and F-terms contributions, $V_{h-s} = V_D + V_F$, where

$$V_D = \frac{g'^2}{8} \left(1 + \frac{2M_1}{F} \frac{\phi_X + \phi_X^*}{2} \right)^{-1} (|H_u|^2 - |H_d|^2)^2 + \frac{g_2^2}{8} \left(1 + \frac{2M_2}{F} \frac{\phi_X + \phi_X^*}{2} \right)^{-1} \left(H_u^\dagger \sigma^i H_u + H_d^\dagger \sigma^i H_d \right)^2, \quad (3)$$

$$V_F = \left| - \left(\mu + \frac{B_\mu}{F} \phi_X \right) \epsilon_{ij} H_d^i + \frac{m_{H_u}^2}{F} \phi_X H_u^{*j} \right|^2 + \left| - \left(\mu + \frac{B_\mu}{F} \phi_X \right) \epsilon_{ij} H_u^j + \frac{m_{H_d}^2}{F} \phi_X H_d^{*i} \right|^2 + m_X^2 |\phi_X|^2 + m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + B_\mu \left\{ H_d \cdot H_u + (H_d \cdot H_u)^\dagger \right\}, \quad (4)$$

up to $\mathcal{O}(1/F)$. For $\mathcal{O}(1/F^2)$ terms, see Appendix D. Note that, we write the scalar components of up-type and down-type Higgs, H_u and H_d , by the same characters as that of the superfields. The vacuum expectation values v_d , v_u and v_X are defined as

$$H_d = \begin{pmatrix} (h_d^0 + iA_d + v_d)/\sqrt{2} \\ H_d^- \end{pmatrix}, \quad H_u = \begin{pmatrix} H_u^+ \\ (h_u^0 + iA_u + v_u)/\sqrt{2} \end{pmatrix}, \quad \phi_X = (s_X + ia_X + v_X)/\sqrt{2}, \quad (5)$$

where $v^2 = v_d^2 + v_u^2 \sim (246\text{GeV})^2$ and we define $\tan \beta = v_u/v_d$.

The vacuum conditions, up to $\mathcal{O}(1/F)$, are obtained as

$$\frac{1}{2} m_Z^2 = -\mu^2 + \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2 \beta}{\tan^2 \beta - 1}, \quad (6)$$

$$\sin 2\beta = -\frac{2B_\mu}{m_A^2},$$

$$v_X = -\frac{1}{2\sqrt{2}F} \frac{v^2}{m_X^2} \left[(m_A^2 - 2\mu^2) \mu \sin 2\beta + 2\mu B_\mu - \frac{(\cos 2\beta)^2}{2c_W^2} m_W^2 (s_W^2 M_1 + c_W^2 M_2) \right],$$

the definition of m_A^2 is the same as that of the usual MSSM, $m_A^2 = m_{H_d}^2 + m_{H_u}^2 + 2\mu^2$. As it can be seen in Eq. (6), neglecting $\mathcal{O}(1/F^2)$ and further higher order terms results in the first two conditions being the same as that of MSSM. We can neglect v_X hereafter since it is $1/F$ suppressed and all terms which accompany v_X are further suppressed by factor $1/F$.

3.2. Neutral scalar mass matrix

The neutral scalar mass terms are written as

$$\mathcal{L} \supset -\frac{1}{2} (h_u^0 \ h_d^0 \ s_X) \begin{pmatrix} m_A^2 \cos^2 \beta + m_Z^2 \sin^2 \beta & -(m_A^2 + m_Z^2) \cos \beta \sin \beta & (m_{\text{higgs}^0}^2)_{13} \\ -(m_A^2 + m_Z^2) \cos \beta \sin \beta & m_A^2 \sin^2 \beta + m_Z^2 \cos^2 \beta & (m_{\text{higgs}^0}^2)_{23} \\ (m_{\text{higgs}^0}^2)_{31} & (m_{\text{higgs}^0}^2)_{32} & m_X^2 \end{pmatrix} \begin{pmatrix} h_u^0 \\ h_d^0 \\ s_X \end{pmatrix},$$

$$(m_{\text{higgs}^0}^2)_{13} = (m_{\text{higgs}^0}^2)_{31} = \frac{v}{\sqrt{2}F} [(-2\mu^2 + m_A^2 \cos 2\beta)\mu \cos \beta + m_Z^2(s_W^2 M_1 + c_W^2 M_2) \cos 2\beta \sin \beta],$$

$$(m_{\text{higgs}^0}^2)_{23} = (m_{\text{higgs}^0}^2)_{32} = -\frac{v}{\sqrt{2}F} [(2\mu^2 + m_A^2 \cos 2\beta)\mu \sin \beta + m_Z^2(s_W^2 M_1 + c_W^2 M_2) \cos 2\beta \cos \beta], \quad (7)$$

up to $\mathcal{O}(1/F)$. By the usual MSSM rotation,

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} h_u^0 \\ h_d^0 \end{pmatrix}, \quad \tan 2\alpha = \tan 2\beta \frac{m_A^2 + m_Z^2}{m_A^2 - m_Z^2}, \quad (8)$$

Eq. (7) is rewritten as

$$\mathcal{L} \supset -\frac{1}{2} (h \ H \ s_X) \begin{pmatrix} m_h^2 & 0 & (m_{\text{higgs}^0}^2)'_{13} \\ 0 & m_H^2 & (m_{\text{higgs}^0}^2)'_{23} \\ (m_{\text{higgs}^0}^2)'_{31} & (m_{\text{higgs}^0}^2)'_{32} & m_X^2 \end{pmatrix} \begin{pmatrix} h \\ H \\ s_X \end{pmatrix}, \quad (9)$$

$$m_{h,H}^2 = \frac{1}{2}(m_Z^2 + m_A^2) \mp \frac{1}{2}\sqrt{(m_Z^2 - m_A^2)^2 + 4m_Z^2 m_A^2 (\sin 2\beta)^2}. \quad (10)$$

In the limit $m_A \gg m_Z$, $\sin 2\alpha = -\sin 2\beta$, the off-diagonal components can be written as

$$(m_{\text{higgs}^0}^2)'_{13} = (m_{\text{higgs}^0}^2)'_{31} = \frac{v}{\sqrt{2}F} [2\mu^3 \sin 2\beta + m_Z^2(s_W^2 M_1 + c_W^2 M_2)(\cos 2\beta)^2],$$

$$(m_{\text{higgs}^0}^2)'_{23} = (m_{\text{higgs}^0}^2)'_{32} = \frac{v \cos 2\beta}{\sqrt{2}F} [(m_A^2 - 2\mu^2)\mu + m_Z^2(s_W^2 M_1 + c_W^2 M_2) \sin 2\beta]. \quad (11)$$

We define the mass eigenbasis $\phi_i = (\phi_1, \phi_2, \phi_3)$ as

$$\phi_i = S_{ij} h_j, \quad (12)$$

where $h_i = (h, H, s_X)$. The mass terms are written as

$$\mathcal{L} \supset -\frac{1}{2}m_i^2\phi_i^2, \quad (13)$$

where $m_{1,2,3}$ are in ascending order. These masses are not different from the diagonal elements of Eq. (9) up to $\mathcal{O}(1/F)$, i.e, m_h and m_H are the same as the light and heavy Higgs boson masses of MSSM, respectively.

This approximation is not valid when $g^2 < (m_{\text{SUSY}}^2/F)^2$ as $\mathcal{O}(1/F^2)$ contributions to the lightest Higgs boson mass cannot be negligible. For example, the tree level lightest Higgs boson mass up to $\mathcal{O}(1/F^2)$, in the limit of large m_X (or large m_A) and large $\tan\beta$, is obtained as

$$m_h^2 \sim m_Z^2 + \frac{2v^2}{F^2}\mu^4, \quad (14)$$

where we have neglected terms which are proportional to gauge coupling in $\mathcal{O}(1/F^2)$ terms. Thus, if $\mu/\sqrt{F} \sim 0.5$ the lightest Higgs mass can be ~ 125 GeV at tree level.

Therefore we include $\mathcal{O}(1/F^2)$ terms only in the neutral Higgs boson mass matrices in our numerical analysis in Section 5. The $\mathcal{O}(1/F^2)$ terms affect the value of the lightest Higgs mass only for large values of μ . If μ term is very large, the obtained lightest Higgs boson mass is larger than the observed Higgs mass. However, in a general low-scale SUSY breaking scenario additional higher dimensional terms which do not include goldstino superfield can contribute to the Higgs mass. If there are such additional terms, the bound would change.

3.3. Pseudo scalar mass matrix

The pseudo scalar mass matrix is written as

$$\mathcal{L} \supset -\frac{1}{2}(A_u \ A_d \ a_X) \begin{pmatrix} m_A^2 \cos^2 \beta & m_A^2 \sin \beta \cos \beta & \frac{m_A^2 - 2\mu^2}{\sqrt{2}F} \mu v \cos \beta \\ m_A^2 \sin \beta \cos \beta & m_A^2 \sin^2 \beta & \frac{m_A^2 - 2\mu^2}{\sqrt{2}F} \mu v \sin \beta \\ \frac{m_A^2 - 2\mu^2}{\sqrt{2}F} \mu v \cos \beta & \frac{m_A^2 - 2\mu^2}{\sqrt{2}F} \mu v \sin \beta & m_X^2 \end{pmatrix} \begin{pmatrix} A_u \\ A_d \\ a_X \end{pmatrix}, \quad (15)$$

up to $\mathcal{O}(1/F)$. At this order, would-be Nambu-Goldstone boson is the same as the usual MSSM, $G^0 = \cos\beta A_d - \sin\beta A_u$, then, by the rotation

$$\begin{pmatrix} A_d \\ A_u \\ a_X \end{pmatrix} = \begin{pmatrix} \cos \beta & \sin \beta & 0 \\ -\sin \beta & \cos \beta & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} G^0 \\ A \\ a_X \end{pmatrix}, \quad (16)$$

Eq. (15) is rewritten as

$$\mathcal{L} \supset -\frac{1}{2} (A \ a_X) \begin{pmatrix} m_A^2 & \frac{m_A^2 - 2\mu^2}{\sqrt{2}F} \mu v \\ \frac{m_A^2 - 2\mu^2}{\sqrt{2}F} \mu v & m_X^2 \end{pmatrix} \begin{pmatrix} A \\ a_X \end{pmatrix}. \quad (17)$$

The mass eigenbasis $a_i = (a_1, a_2)$ is defined as

$$a_i = A_{ij} A_j, \quad (18)$$

where $A_i = (A, a_X)$. Then, the mass terms are written as

$$\mathcal{L} \supset -\frac{1}{2} m_{ai}^2 a_i^2, \quad (19)$$

where $m_{a1,2} (m_A, m_{aX} = m_X)$ are in ascending order. Thus, the pseudo-scalar Higgs mass is the same as the MSSM pseudo scalar Higgs mass up to $\mathcal{O}(1/F)$. For example, when $m_A < m_{aX}$,

$$A_{ij} = \begin{pmatrix} \cos \theta_a & -\sin \theta_a \\ \sin \theta_a & \cos \theta_a \end{pmatrix}_{ij}, \quad \tan 2\theta_a = -\frac{\sqrt{2}\mu v}{F} \frac{m_A^2 - 2\mu^2}{m_A^2 - m_X^2}. \quad (20)$$

3.4. Charged scalar mass matrix

The charged scalar mass matrix is written as

$$\mathcal{L} \supset - (H_u^+ \ H_d^+) \begin{pmatrix} (m_A^2 + m_W^2) \cos^2 \beta & (m_A^2 + m_W^2) \sin \beta \cos \beta \\ (m_A^2 + m_W^2) \sin \beta \cos \beta & (m_A^2 + m_W^2) \sin^2 \beta \end{pmatrix} \begin{pmatrix} H_u^- \\ H_d^- \end{pmatrix}, \quad (21)$$

up to $\mathcal{O}(1/F)$ and this is the same as the charged Higgs mass in MSSM. Eq. (21) can be redefined in terms of the would-be Nambu-Goldstone boson G^- and the physical charged Higgs boson H^- by the following rotation

$$\begin{pmatrix} H_u^- \\ H_d^- \end{pmatrix} = \begin{pmatrix} \cos \beta & -\sin \beta \\ \sin \beta & \cos \beta \end{pmatrix} \begin{pmatrix} H^- \\ G^- \end{pmatrix}, \quad (22)$$

yielding the mass term

$$\mathcal{L} \supset -(m_A^2 + m_W^2) H^+ H^-, \quad (23)$$

up to $\mathcal{O}(1/F)$.[§]

[§] However, if we take into account higher orders in $1/F$ expansion, the mixing angle would change.

4. GAUGINO-HIGGSINO-GOLDSTINO MASS MATRICES

Through the electroweak symmetry breaking, the fermionic component of the goldstino superfield mixes with gauginos and Higgsinos. In this section, we write the neutralino and chargino mass matrices and define their mass eigenstates.

4.1. Neutralino mass matrix

From Eq. (2), the neutralino mass terms are obtained as

$$\mathcal{L} \supset -\frac{1}{2} \begin{pmatrix} \tilde{B} & \tilde{W} & \tilde{H}_d^0 & \tilde{H}_u^0 & \psi_X \end{pmatrix} M_{\tilde{N}} \begin{pmatrix} \tilde{B} \\ \tilde{W} \\ \tilde{H}_d^0 \\ \tilde{H}_u^0 \\ \psi_X \end{pmatrix} + \text{h.c.}, \quad (24)$$

$$M_{\tilde{N}} = \begin{pmatrix} M_1 & 0 & -m_Z s_W \cos \beta & m_Z s_W \sin \beta & (M_{\tilde{N}})_{15} \\ 0 & M_2 & m_Z c_W \cos \beta & -m_Z c_W \sin \beta & (M_{\tilde{N}})_{25} \\ -m_Z s_W \cos \beta & m_Z c_W \cos \beta & 0 & \mu & (M_{\tilde{N}})_{35} \\ m_Z s_W \sin \beta & -m_Z c_W \sin \beta & \mu & 0 & (M_{\tilde{N}})_{45} \\ (M_{\tilde{N}})_{51} & (M_{\tilde{N}})_{52} & (M_{\tilde{N}})_{53} & (M_{\tilde{N}})_{54} & 0 \end{pmatrix},$$

where

$$\begin{aligned} (M_{\tilde{N}})_{15} &= (M_{\tilde{N}})_{51} = \frac{1}{8\sqrt{2}F} v \cos 2\beta s_W m_Z M_1, \\ (M_{\tilde{N}})_{25} &= (M_{\tilde{N}})_{52} = -\frac{1}{8\sqrt{2}F} v \cos 2\beta c_W m_Z M_2, \\ (M_{\tilde{N}})_{35} &= (M_{\tilde{N}})_{53} = \frac{1}{2\sqrt{2}F} v \cos \beta \left(\mu^2 + \frac{1}{2} m_Z^2 \cos 2\beta \right), \\ (M_{\tilde{N}})_{45} &= (M_{\tilde{N}})_{54} = \frac{1}{2\sqrt{2}F} v \sin \beta \left(\mu^2 - \frac{1}{2} m_Z^2 \cos 2\beta \right), \end{aligned} \quad (25)$$

up to $\mathcal{O}(1/F)$. We write the mass eigenbasis as $\tilde{\chi} = (\tilde{\chi}_0, \tilde{\chi}_1, \tilde{\chi}_2, \tilde{\chi}_3, \tilde{\chi}_4)^T$ where $m_{\tilde{\chi}_i} < m_{\tilde{\chi}_j}$ with $i < j$ and $\tilde{\chi}_0$ corresponds to goldstino. It is defined as

$$\tilde{\chi}_i = N_{ij} \tilde{N}_j^0 = \xi_i N'_{ij} \tilde{N}_j^0, \quad (26)$$

where N'_{ij} is a rotation matrix which diagonalizes the mass matrix and $\tilde{N}^0 = (\tilde{B}, \tilde{W}, \tilde{H}_d^0, \tilde{H}_u^0, \psi_X)^T$, respectively. The ξ_i is 1 (i) for positive (negative) eigenvalues of the diagonalized mass matrix. The mass eigenvalues are the same as MSSM with massless goldstino up to $\mathcal{O}(1/F)$.

4.2. Chargino mass matrix

The chargino mass matrix is the same as that of MSSM up to $\mathcal{O}(1/F)$:

$$\mathcal{L} \supset - \begin{pmatrix} \tilde{W}^+ & \tilde{H}_u^+ \end{pmatrix} \begin{pmatrix} M_2 & \sqrt{2}m_W \cos \beta \\ \sqrt{2}m_W \sin \beta & -\mu \end{pmatrix} \begin{pmatrix} \tilde{W}^- \\ \tilde{H}_d^- \end{pmatrix} + \text{h.c.} \quad (27)$$

We describe the mass eigenstates as $\tilde{\chi}^- = (\tilde{\chi}_1^-, \tilde{\chi}_2^-)^T$ where $m_{\tilde{\chi}_1^-} < m_{\tilde{\chi}_2^-}$ and defined as

$$\tilde{\chi}_{Li}^- = C_{ij}^L \tilde{C}_{Lj}^- \quad \text{and} \quad \tilde{\chi}_{Ri}^- = C_{ij}^R \tilde{C}_{Rj}^- = \epsilon_i C_{ij}^{R'} \tilde{C}_{Rj}^-. \quad (28)$$

C_{ij}^L and $C_{ij}^{R'}$ are the rotation matrices which diagonalize the mass matrix and $\tilde{C}_L^- = (\tilde{W}^-, \tilde{H}_d^-)^T$ and $\tilde{C}_R^- = (\tilde{W}^-, \tilde{H}_u^-)^T$, respectively. ϵ_i is 1 (−1) for positive (negative) eigenvalues of the diagonalized mass matrix obtained by using C_{ij}^L and C_{ij}^R .

5. PRODUCTION AND DECAY OF THE SGOLDSTINO

We now turn to study the production and decay of sgoldstino at the LHC. First, we discuss the partial widths of sgoldstino and pseudo-sgoldstino using approximations. Then, we present the numerical results for production cross section and branching ratios.

5.1. Partial decay widths

In this subsection, we discuss the partial decay widths of sgoldstino and pseudo-sgoldstino assuming these are much heavier than Z boson and mixing with MSSM Higgs bosons is not large, for simplicity. The full analytical expressions for the partial widths are compiled in Appendix C.

Gauge boson branch

The partial decay width to a pair of gluons gg which contributes not only to the decay but also to the production at the LHC is obtained to be

$$\Gamma(\phi \rightarrow gg) \approx \frac{1}{4\pi} \frac{M_3^2 m_\phi^3}{F^2}, \quad (29)$$

where $\phi = s, a$ [¶]. Then we can obtain the following relation,

$$\begin{aligned} & \Gamma(\phi \rightarrow gg) : \Gamma(\phi \rightarrow \gamma\gamma) : \Gamma(\phi \rightarrow \gamma Z) \\ & \approx M_3^2 : \frac{1}{8} (c_W^2 M_1 + s_W^2 M_2)^2 : \frac{1}{4} s_W^2 c_W^2 (M_1 - M_2)^2. \end{aligned} \quad (30)$$

For massive boson final states, if the transverse modes dominate, the partial decay widths is obtained to be

$$\begin{aligned} & \Gamma(\phi \rightarrow gg) : \Gamma(\phi \rightarrow W_T W_T) : \Gamma(\phi \rightarrow Z_T Z_T) \\ & \approx M_3^2 : \frac{1}{4} M_2^2 : \frac{1}{8} (s_W^2 M_1 + c_W^2 M_2)^2. \end{aligned} \quad (31)$$

On the other hand, if the longitudinal mode is dominant, the partial decay widths can be obtained by the would-be Goldstone boson interaction through the equivalence theorem. The interactions of sgoldstino with the would-be Goldstone boson G^0 is given by

$$\mathcal{L} \supset \frac{1}{2\sqrt{2}F} [2\mu^3 \sin 2\beta + m_Z^2 (s_W^2 M_1 + c_W^2 M_2) (\cos 2\beta)^2] s_X G^0 G^0, \quad (32)$$

up to $\mathcal{O}(1/F)$. After dropping the term proportional to m_Z^2 , the decay width is obtained to be

$$\begin{aligned} \Gamma(s \rightarrow G^0 G^0) & \approx \frac{1}{8\pi m_s} \left[\frac{1}{2\sqrt{2}F} (2\mu^3 \sin 2\beta) \right]^2 \\ & = \frac{1}{16\pi} \frac{\mu^6}{m_s F^2} (\sin 2\beta)^2. \end{aligned} \quad (33)$$

The ratio of partial decay widths

$$\Gamma(s_X \rightarrow G^0 G^0) : \Gamma(s_X \rightarrow W_L W_L) : \Gamma(s_X \rightarrow Z_L Z_L) \approx 1 : 2 : 1. \quad (34)$$

There is no pseudo-sgoldstino interactions with $G^0 G^0$ in the absence of CP violation.

Higgs boson branch

Assuming $m_Z \ll (\mu \text{ and } m_A)$ and $m_Z M_a \ll \mu^2$, the decay width of sgoldstino to a pair of lightest CP -even higgs h is

$$\begin{aligned} \Gamma(s \rightarrow hh) & \approx \frac{1}{8\pi m_s} \left[\frac{\mu}{2\sqrt{2}F} \{ (m_A^2 - 2\mu^2) \sin 2\alpha + m_A^2 \sin 2\beta \} \right]^2 \\ & \approx \frac{1}{16\pi} \frac{\mu^6}{m_s F^2} (\sin 2\beta)^2. \end{aligned} \quad (35)$$

[¶] The $s(a)$ denotes a sgoldstino(pseudo-sgoldstino)-dominant particle in $\phi_i(a_i)$, which are defined in Eq. (12)(Eq. (18)).

The second line of Eq. (35) can be obtained by using $(\sin 2\alpha) \sim -(\sin 2\beta)$. In such a limit, the interactions $s_X hh$ and $s_X G^0 G^0$ are the same at the leading order. Then, the following relation is obtained

$$\Gamma(s \rightarrow hh) : \Gamma(s \rightarrow W_L W_L) : \Gamma(s \rightarrow Z_L Z_L) \approx 1 : 2 : 1. \quad (36)$$

On the other hand, the pseudo-sgoldstino does not decay into hh in the absence of CP violation.

If kinematically allowed, decays to other Higgs bosons also exist. By the same approximation used to derive Eq. (35), the decay widths of s_X to heavy Higgs bosons are

$$\Gamma(s \rightarrow HH) \approx \frac{1}{16\pi} \frac{\mu^2(m_A^2 - \mu^2)^2}{m_s F^2} (\sin 2\beta)^2, \quad (37)$$

and

$$\Gamma(s \rightarrow H^+ H^-)/2 \approx \Gamma(s \rightarrow AA) \approx \Gamma(s \rightarrow HH), \quad (38)$$

where we have assumed $m_s \gg m_A$ for simplicity. On the other hand,

$$\begin{aligned} \Gamma(s \rightarrow hH) &\approx \frac{1}{32\pi} \frac{\mu^2(m_A^2 - 2\mu^2)^2}{m_s F^2} (\cos 2\beta)^2, \\ \Gamma(a \rightarrow hA) &\approx \frac{1}{32\pi} \frac{\mu^2(m_A^2 - 2\mu^2)^2}{m_a F^2}. \end{aligned} \quad (39)$$

Note that there is no $1/\tan \beta$ suppression in Eq. (39). Thus, the partial width of $s_X \rightarrow hH$ is larger than the other Higgs boson branches and the longitudinal mode of WW/ZZ in the limit of large $\tan \beta$.

Fermion and sfermion branch

Sgoldstino interactions with SM fermions is proportional to $m_f A_f / (y_f F)$ as shown in Eq. (59) in Appendix A. However, sgoldstino-fermion-fermion couplings originating from mixing with MSSM Higgs bosons can contribute at the same order. In the limit $m_Z \ll m_A \ll m_X$ or $m_Z \ll m_X \ll m_A$, $(\sin 2\alpha) \sim -(\sin 2\beta)$, the decay widths of sgoldstino to SM fermions take the form

$$\begin{aligned} \Gamma(s \rightarrow \bar{t}t) &\approx \frac{3}{16\pi} \frac{m_s m_t^2}{F^2} \left[\frac{A_t}{y_t} + 2 \frac{\mu^3}{m_s^2} \sin 2\beta - \left(\frac{m_A^2 - 2\mu^2}{m_s^2 - m_A^2} \right) \frac{\mu \cos 2\beta}{\tan \beta} \right]^2, \\ \Gamma(s \rightarrow \bar{b}b) &\approx \frac{3}{16\pi} \frac{m_s m_b^2}{F^2} \left[\frac{A_b}{y_b} + 2 \frac{\mu^3}{m_s^2} \sin 2\beta + \left(\frac{m_A^2 - 2\mu^2}{m_s^2 - m_A^2} \right) \mu \cos 2\beta \tan \beta \right]^2. \end{aligned} \quad (40)$$

Note that the third term in the expression for $\Gamma(s_X \rightarrow \bar{b}b)$ in Eq. (40) are $\tan \beta$ enhanced. In the same limit as above, the decay widths of pseudo-sgoldstino to SM fermions is written as

$$\begin{aligned}\Gamma(a \rightarrow \bar{t}t) &\approx \frac{3}{16\pi} \frac{m_a m_t^2}{F^2} \left[\frac{A_t}{y_t} + \left(\frac{m_A^2 - 2\mu^2}{m_a^2 - m_A^2} \right) \frac{\mu}{\tan \beta} \right]^2, \\ \Gamma(a \rightarrow \bar{b}b) &\approx \frac{3}{16\pi} \frac{m_a m_b^2}{F^2} \left[\frac{A_b}{y_b} + \left(\frac{m_A^2 - 2\mu^2}{m_a^2 - m_A^2} \right) \mu \tan \beta \right]^2.\end{aligned}\quad (41)$$

Similar to the case of $\Gamma(s \rightarrow \bar{b}b)$, there is $\tan \beta$ enhancement arising from mixing in $\Gamma(a \rightarrow \bar{b}b)$. Estimating the width of the tau branch is straightforward.

Next, we discuss partial widths for sfermion final states. As shown in Appendix A, $s_X \tilde{f}_L \tilde{f}_L$ and $s_X \tilde{f}_R \tilde{f}_R$ couplings are proportional v^2/F . On the other hand, the $\phi \tilde{f}_L \tilde{f}_R$ couplings are proportional v , thus making them larger than $s_X \tilde{f}_L \tilde{f}_L$ and $s_X \tilde{f}_R \tilde{f}_R$ couplings. Assuming left-right mixing is small in the sfermion sector,

$$\begin{aligned}\Gamma(s \rightarrow \tilde{t}_1^* \tilde{t}_2 + \tilde{t}_1 \tilde{t}_2^*) &\approx \frac{3}{16\pi} \frac{m_t^2}{m_s F^2} \frac{1}{\tan^2 \beta} \left[\left(\frac{A_t}{y_t} \mu + \frac{1}{2} m_A^2 \sin 2\beta \right) - 2 \frac{\mu^3}{m_s^2} \sin 2\beta \left(\frac{A_t}{y_t} \tan \beta + \mu \right) \right. \\ &\quad \left. + \left(\frac{m_A^2 - 2\mu^2}{m_s^2 - m_A^2} \mu \cos 2\beta \right) \left(\frac{A_t}{y_t} - \mu \tan \beta \right) \right]^2,\end{aligned}\quad (42)$$

where kinetic suppression is neglected assuming $m_{\tilde{t}_{1(2)}} \ll m_s$. On the other hand, if the mixing is maximally large,

$$\begin{aligned}\Gamma(s \rightarrow \tilde{t}_1^* \tilde{t}_1) &\approx \frac{3}{32\pi} \frac{m_t^2}{m_s F^2} \frac{1}{\tan^2 \beta} \left[\left(\frac{A_t}{y_t} \mu + \frac{1}{2} m_A^2 \sin 2\beta \right) - 2 \frac{\mu^3}{m_s^2} \sin 2\beta \left(\frac{A_t}{y_t} \tan \beta + \mu \right) \right. \\ &\quad \left. + \left(\frac{m_A^2 - 2\mu^2}{m_s^2 - m_A^2} \mu \cos 2\beta \right) \left(\frac{A_t}{y_t} - \mu \tan \beta \right) \right]^2.\end{aligned}\quad (43)$$

In the same limit as above, the partial decay widths of pseudo-sgoldstino to sfermions is given by,

$$\begin{aligned}\Gamma(a \rightarrow \tilde{t}_1^* \tilde{t}_2 + \tilde{t}_1 \tilde{t}_2^*) &\approx \frac{3}{16\pi} \frac{m_t^2}{m_a F^2} \frac{1}{\tan^2 \beta} \left[\left(\frac{A_t}{y_t} \mu + \frac{1}{2} m_A^2 \sin 2\beta \right) \right. \\ &\quad \left. - \left(\frac{m_A^2 - 2\mu^2}{m_a^2 - m_A^2} \mu \right) \left(\frac{A_t}{y_t} - \mu \tan \beta \right) \right]^2,\end{aligned}\quad (44)$$

Estimating sbottom and stau branch is straightforward. One of the main difference is $m_t/\tan \beta \rightarrow m_{b(\tau)} \tan \beta$.

Gaugino-Higgsino-Gravitino branch

The partial decay width of the gravitino final state can be written as

$$\Gamma(\phi \rightarrow \tilde{G} \tilde{G}) \approx \frac{m_\phi^5}{32\pi F^2},\quad (45)$$

which implies that the branching ratio can be large when sgoldstino is heavy.

Assuming sgoldstino-Higgs mixing is small, we also present the decay width of sgoldstino to pure higgsino final states

$$\Gamma(\phi \rightarrow \tilde{H}_1^0 \tilde{H}_2^0) \approx \Gamma(\phi \rightarrow \tilde{H}^+ \tilde{H}^-) \approx \frac{1}{64\pi} m_\phi \frac{m_A^4 \sin^2 2\beta}{F^2}, \quad (46)$$

where kinetic suppression is neglected assuming sgoldstino is much heavier than higgsino.

5.2. Production cross section

Sgoldstino and pseudo-sgoldstino are mainly produced through the gluon fusion process at the LHC. The corresponding decay width is obtained to be $\Gamma(s \rightarrow gg) \sim (M_3/F)^2 m_s^3 / (4\pi)$, if sgoldstino-MSSM Higgs mixing is not very large. Then, the production cross section of sgoldstino depends on the ratio of gluino mass and F , $1/\Lambda = M_3/F$.

The production cross section of sgoldstino is presented in Fig. 1. To calculate the cross sections we use MadGraph 5 [31, 32] with leading order NNPDF2.3 [33] and Feynrules [34] by approximating the total decay width of sgoldstino to be $\Gamma(s \rightarrow gg)$. The case of pseudo-sgoldstino is similar.

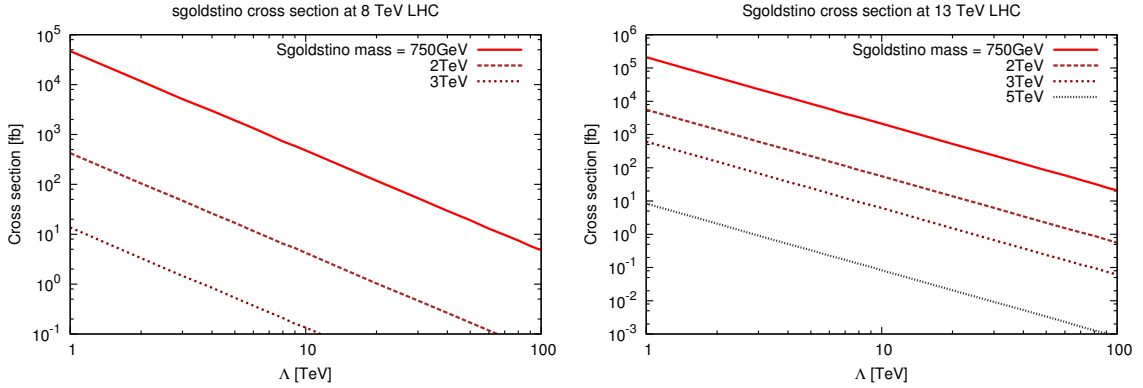


FIG. 1. Production cross section of the sgoldstino s_X at $\sqrt{s} = 8$ TeV (left) and $\sqrt{s} = 13$ TeV (right). The x-axis, Λ , denotes $1/\Lambda = M_3/F$. In the left (right) figure, the sgoldstino mass is 3, 2 and 0.75 TeV (5, 3, 2 and 0.75 TeV) from below.

5.3. Branching ratio

In the final part of the section we discuss the branching ratios of sgoldstino and pseudo-sgoldstino to various final states. Branching ratios are mostly determined by the ratio of soft

masses and \sqrt{F} **. The discussion is illustrated using sample points shown in Table I with $\sqrt{F} = 5$ TeV and $\tan\beta = 10$. Sfermion soft masses are taken to be universal. The A term (A_f/y_f) are also taken to be universal which are determined by the requirement of a light Higgs of mass 125 GeV at each parameter point.

Parameter (in TeV)	Sample point				
	I	II	III	IV	V
μ	-2	-2	-2	-0.2	-2
m_A	4	4	4	4	0.3
$m_{\tilde{f}}$	1	1	2	2	2
M_3	2	2	2	2	2
M_2	2	0.6	2	2	2
M_1	1.5	0.3	1.5	1.5	1.5

TABLE I. Sample points.

For sample point I, branching ratios of sgoldstino and pseudo-sgoldstino to various final states are shown in Fig. 2. As $\Gamma(\phi \rightarrow gg) \propto M_3^2 m_\phi^3 / F^2$ and $\Gamma(\phi \rightarrow \tilde{G}\tilde{G}) \propto m_\phi^5 / F^2$ (see discussion in Sec 5.1), the branching ratio $\phi \rightarrow \tilde{G}\tilde{G}$ becomes large in the heavy sgoldstino (pseudo-sgoldstino) region. For small sgoldstino masses, Higgs-sgoldstino mixing becomes prominent (since μ is large we cannot neglect higgs-sgoldstino mixing) and enhances not only the hh mode but also the longitudinal modes of weak gauge bosons as given by Eqs. (35) and (36). On the other hand, there is no such enhancements in the case of pseudo-sgoldstino due to the absence of CP violation.

Since the partial widths for transverse gauge boson modes can be written in the form of Eqs. (30) and (31), it is easy to understand how the branching ratios change with the variation of gaugino masses. Sample point II differs from sample point I only with respect to gaugino masses, where M_2 is 0.3 times M_2 of sample point I and M_1 is 0.2 times M_1 of sample point I, respectively. The results are presented in Fig. 3 for sgoldstino and pseudo-sgoldstino.

In Fig. 4, we show the branching ratio of sgoldstino and pseudo-sgoldstino for sample point III. Here, sfermion masses ($m_{\tilde{f}}$) are set to 2 TeV instead of 1 TeV in sample point I. This change impacts the ratio A/\sqrt{F} by making it large thereby enhancing the $t\bar{t}$ mode which depends on $m_f A_f / (y_f F)$ as prescribed in Eq. (40) and Eq. (41).

We also consider the case of small μ (sample point IV), where $|\mu|$ is 0.2 TeV instead of 2 TeV as in sample point I. The results are depicted in Fig. 5. Since Higgs-sgoldstino mixing

** An exceptional example would be the branching to fermion final states, which depends on v/\sqrt{F} as discussed previously.

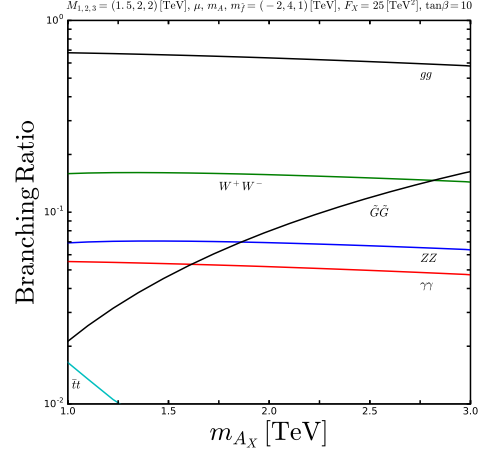
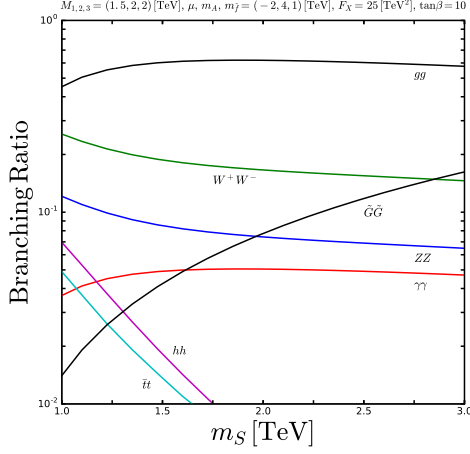


FIG. 2. Sample Point I: branching ratio of the sgoldstino (left panel) and pseudo-sgoldstino (right panel) at $\sqrt{F} = 5$ TeV, $(\mu, m_A, m_{\tilde{f}}) = (-2, 4, 1)$ TeV and $(M_3, M_2, M_1) = (2, 2, 1.5)$ TeV with $\tan\beta = 10$.

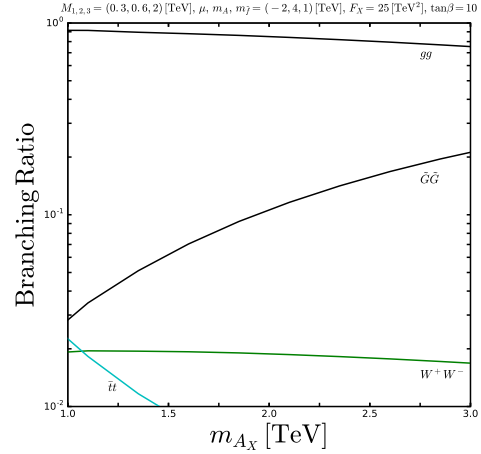
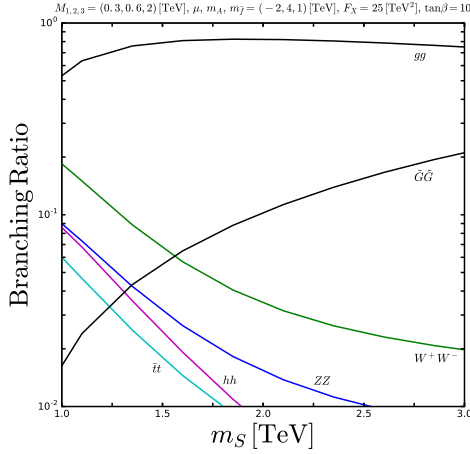


FIG. 3. Sample Point II: branching ratio of the sgoldstino (left panel) and pseudo-sgoldstino (right panel) at $\sqrt{F} = 5$ TeV, $(\mu, m_A, m_{\tilde{f}}) = (-2, 4, 1)$ TeV and $(M_3, M_2, M_1) = (2, 0.6, 0.3)$ TeV with $\tan\beta = 10$.

depends on the value of the μ , the branching ratio of hh and longitudinal modes of WW/ZZ

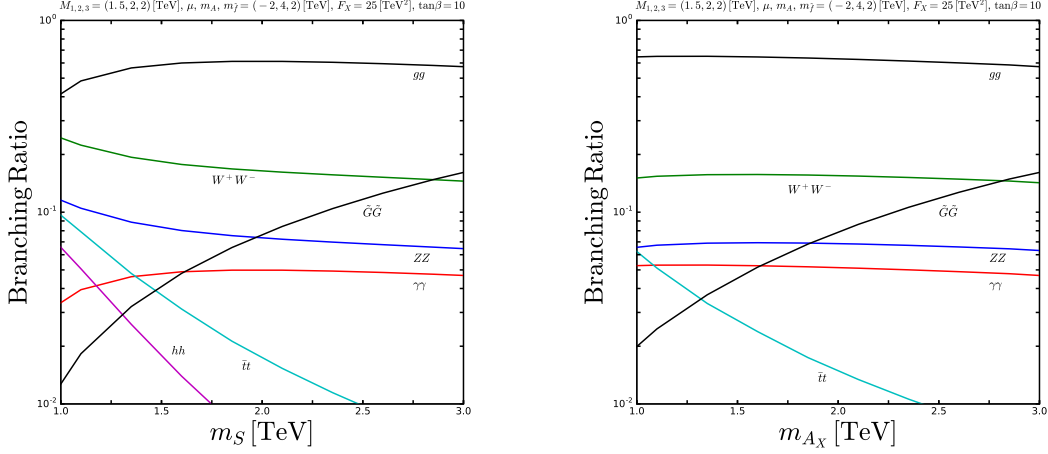


FIG. 4. Sample Point III: branching ratio of the sgoldstino (left panel) and pseudo-sgoldstino (right panel) at $\sqrt{F} = 5$ TeV, $(\mu, m_A, m_{\bar{f}}) = (-2, 4, 2)$ TeV and $(M_3, M_2, M_1) = (2, 2, 1.5)$ TeV with $\tan\beta = 10$.

is not large, see Eqs. (35) and (36). On the other hand, small values of μ results in light higgsino masses, thus this channel is kinematically allowed. Branching to Higgsino final states can be large since the decay width depends on m_A^4/F^2 as shown in Eq. (46).

Finally, we present results for sample point V in Fig. 6. The case of small m_A , where m_A is 0.3 TeV instead of 4 TeV in sample point I. Unlike the hh decay mode of sgoldstino, the decay width of hH (hA) is not $\tan\beta$ suppressed and depends on $\mu^2(m_A^2 - 2\mu^2)^2/(m_\phi F^2)$ as shown in Eq. (39). Thus, branching to hH (hA) can be large if kinematically open.

To summarize, the total decay width is not very large for the sample points considered here. If sgoldstino-Higgs mixing is not large, the total width can be extracted from each of the above figures using the approximate analytical expression for the width of $s \rightarrow gg$,

$$\begin{aligned} \Gamma(s \rightarrow gg) &\approx M_3^2 m_s^3 / (4\pi F^2) \\ &\sim 0.5 \text{ GeV} \left(\frac{m_s}{1 \text{ TeV}} \right)^3 \left(\frac{M_3}{2 \text{ TeV}} \right)^2 \left(\frac{5 \text{ TeV}}{\sqrt{F}} \right)^4. \end{aligned} \quad (47)$$

Thus, in the parameter space considered here, the total decay width is smaller than 100 GeV and it can be measured as a narrow resonance at collider experiments.

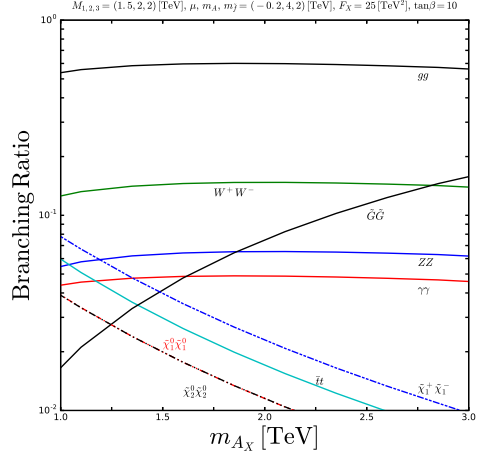
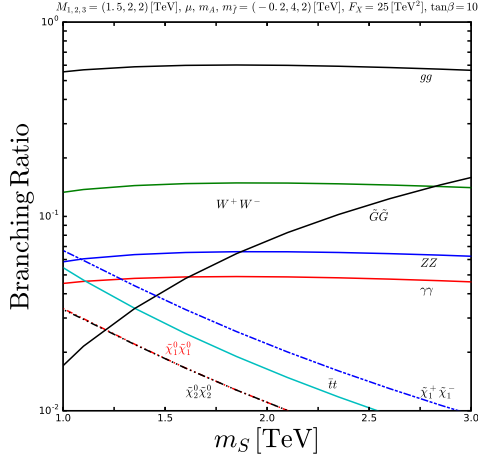


FIG. 5. Sample Point IV: branching ratio of the sgoldstino (left panel) and pseudo-sgoldstino (right panel) at $\sqrt{F} = 5$ TeV, $(\mu, m_A, m_{\tilde{f}}) = (-0.2, 4, 2)$ TeV and $(M_3, M_2, M_1) = (2, 2, 1.5)$ TeV with $\tan\beta = 10$.

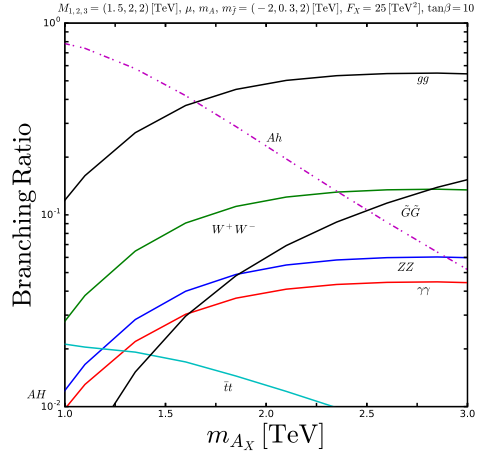
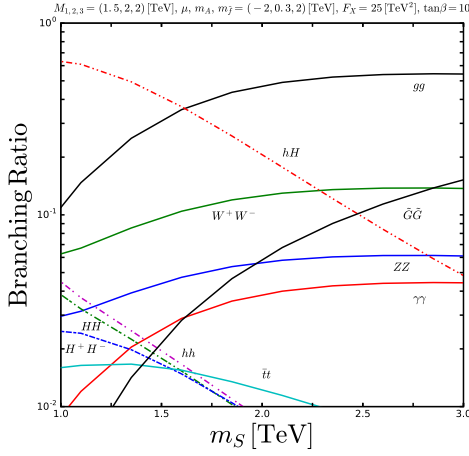


FIG. 6. Sample Point V: branching ratio of the sgoldstino (left panel) and pseudo-sgoldstino (right panel) at $\sqrt{F} = 5$ TeV, $(\mu, m_A, m_{\tilde{f}}) = (-2, 0.3, 2)$ TeV and $(M_3, M_2, M_1) = (2, 2, 1.5)$ TeV with $\tan\beta = 10$.

6. SUMMARY

In supersymmetric extensions of SM, low-scale breaking of SUSY is phenomenologically valid. One of the features of low-scale SUSY breaking is that the hidden sector can be accessible in collider experiments as the couplings between SM and hidden sector are not suppressed by a high-scale mass parameter. Furthermore, there are additional contributions to quartic coupling of the lightest Higgs boson with which we can obtain Higgs mass of 125 GeV at tree level [7, 16, 17, 28].

We have investigated the collider phenomenology of sgoldstino which is the scalar component of the goldstino superfield. We have considered various possible branches of sgoldstino and pseudo-sgoldstino decay in this paper, including that of Higgs bosons, sparticles and particles final state.

We have shown that sgoldstino decays to $s \rightarrow hh$ and longitudinal modes of WW and ZZ can be large if the μ parameter is large. If allowed kinematically, the branching to $s \rightarrow hH$ can be larger than $s \rightarrow hh$.

Finally, we have also discussed other possible collider phenomenology in the low-scale SUSY breaking scenario. In this scenario, the gravitino is very light as $m_{3/2} \sim 6 \times 10^{-3} \text{eV} (\sqrt{F}/(5\text{TeV}))^2$ and they can appear in the final state of SUSY particle production events at the LHC. Furthermore, the gravitino production may also be possible. For example, the gravitino-gluino production would provide large missing E_T events at the LHC although the current constraint is not strong [35].

ACKNOWLEDGMENTS

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APPENDIX A: LAGRANGIAN (BEFORE MIXING)

Here, we write the interaction terms relevant for production and decay of sgoldstino and pseudo-sgoldstino at the LHC. We present the leading ($\mathcal{O}(1/F)$) contributions to sgoldstino production and decay.

Couplings with gg , $\gamma\gamma$ and γZ

Sgoldstino interactions with gg , $\gamma\gamma$ and γZ is given by

$$\begin{aligned}\mathcal{L}_s \supset & (C_{sgg}) s_X G^{\mu\nu} G_{\mu\nu} + (C_{s\gamma\gamma}) s_X F^{\mu\nu} F_{\mu\nu} + (C_{s\gamma Z}) s_X F^{\mu\nu} Z_{\mu\nu} \\ & + (C_{agg}) a_X G^{\mu\nu} \tilde{G}_{\mu\nu} + (C_{a\gamma\gamma}) a_X F^{\mu\nu} \tilde{F}_{\mu\nu} + (C_{a\gamma Z}) a_X F^{\mu\nu} \tilde{Z}_{\mu\nu},\end{aligned}\quad (48)$$

$$\begin{aligned}C_{sgg} &= -C_{agg} = -\frac{1}{2\sqrt{2}} \frac{M_3}{F}, \\ C_{s\gamma\gamma} &= -C_{a\gamma\gamma} = -\frac{1}{2\sqrt{2}} \frac{1}{F} (c_W^2 M_1 + s_W^2 M_2), \\ C_{s\gamma Z} &= -C_{a\gamma Z} = -\frac{1}{\sqrt{2}} \frac{1}{F} s_W c_W (-M_1 + M_2),\end{aligned}$$

where $\tilde{F}_{\mu\nu}$ is a dual field strength, $\tilde{F}_{\mu\nu} = (1/2)\epsilon_{\mu\nu\rho\sigma}\tilde{F}^{\rho\sigma}$. We neglect MSSM HGG term contribution in this paper, as these are suppressed by a loop factor. Since this is small, they are comparable to sGG when the above couplings $M_a/F \sim 10^{-5}(\text{GeV})^{-1}$.

Couplings with WW and ZZ

The sgoldstino interactions with WW and ZZ are written as

$$\begin{aligned}\mathcal{L}_s \supset & (C_{sWW_T}) s_X W^{\mu\nu} W_{\mu\nu} + (C_{aWW_T}) a_X W^{\mu\nu} \tilde{W}_{\mu\nu} \\ & + (C_{sZZ_T}) s_X Z^{\mu\nu} Z_{\mu\nu} + (C_{aZZ_T}) a_X Z^{\mu\nu} \tilde{Z}_{\mu\nu},\end{aligned}\quad (49)$$

$$\begin{aligned}C_{sWW_T} &= -C_{aWW_T} = -\frac{1}{\sqrt{2}} \frac{M_2}{F}, \\ C_{sZZ_T} &= -C_{aZZ_T} = -\frac{1}{2\sqrt{2}} \frac{1}{F} (s_W^2 M_1 + c_W^2 M_2).\end{aligned}$$

The interactions with longitudinal mode, e.g. $(C_{sWW_L}) m_W^2 s_X W^\mu W_\mu$, are $\mathcal{O}(1/F^2)$ terms. MSSM contributions which can affect the phenomenology of sgoldstino via mixing are

$$\begin{aligned}\mathcal{L} \supset & -(\sin(\alpha - \beta)h - \cos(\alpha - \beta)H) \left(g_2 m_W W^{+\mu} W_\mu^- + \frac{1}{2} \frac{g}{c_W} m_Z Z^\mu Z_\mu \right) \\ & = C_{hWW_L} m_W^2 h W^{+\mu} W_\mu^- + C_{HWW_L} m_W^2 H W^{+\mu} W_\mu^- + C_{hZZ_L} m_Z^2 h Z^\mu Z_\mu + C_{HZZ_L} m_Z^2 H Z^\mu Z_\mu.\end{aligned}\quad (50)$$

Couplings with Higgs bosons

The sgoldstino interactions with Higgs bosons are obtained as

$$\begin{aligned}\mathcal{L}_s \supset & (C_{shh}) s_X hh + (C_{sHH}) s_X HH + (C_{shH}) s_X hH + (C_{sAA}) s_X AA + (C_{sH^+H^-}) s_X H^+ H^- \\ & + (C_{ahA}) a_X hA + (C_{aHA}) a_X HA,\end{aligned}\quad (51)$$

$$\begin{aligned}
C_{shh} &= \frac{1}{2\sqrt{2}F} \left[\mu((m_A^2 - 2\mu^2) \sin 2\alpha + m_A^2 \sin 2\beta) \right. \\
&\quad \left. + m_Z^2(s_W^2 M_1 + c_W^2 M_2)(1 - 2 \cos 2\alpha \cos 2\beta + \sin 2\alpha \sin 2\beta) \right], \\
C_{sHH} &= \frac{1}{2\sqrt{2}F} \left[\mu(-(m_A^2 - 2\mu^2) \sin 2\alpha + m_A^2 \sin 2\beta) \right. \\
&\quad \left. + m_Z^2(s_W^2 M_1 + c_W^2 M_2)(1 + 2 \cos 2\alpha \cos 2\beta - \sin 2\alpha \sin 2\beta) \right], \\
C_{shH} &= \frac{1}{2\sqrt{2}F} \left[-2\mu(m_A^2 - 2\mu^2) \cos 2\alpha - m_Z^2(s_W^2 M_1 + c_W^2 M_2)(3 \sin 2(\alpha + \beta) + \sin 2(\alpha - \beta)) \right], \\
C_{sAA} &= \frac{1}{2\sqrt{2}F} \left[2\mu(m_A^2 - \mu^2) \sin 2\beta - m_Z^2(s_W^2 M_1 + c_W^2 M_2)(\cos 2\beta)^2 \right], \\
C_{sH^+H^-} &= \frac{1}{\sqrt{2}F} \left[2\mu(m_A^2 - \mu^2) \sin 2\beta - m_Z^2(s_W^2 M_1(\cos 2\beta)^2 - c_W^2 M_2(1 + (\sin 2\beta)^2)) \right], \\
C_{ahA} &= \frac{1}{\sqrt{2}F} \left[\mu(m_A^2 - 2\mu^2) \sin(\alpha - \beta) \right], \\
C_{aHA} &= \frac{1}{\sqrt{2}F} \left[\mu(-m_A^2 + 2\mu^2) \cos(\alpha - \beta) \right],
\end{aligned}$$

and the MSSM contributions which can affect sgoldstino phenomenology via mixing are

$$\begin{aligned}
\mathcal{L} \supset & -\frac{1}{4} \frac{g}{c_W} m_Z \cos 2\alpha \sin(\alpha + \beta) hhh - \frac{1}{4} \frac{g}{c_W} m_Z \cos 2\alpha \cos(\alpha + \beta) HHH \\
& -\frac{1}{4} \frac{g}{c_W} m_Z (2 \sin 2\alpha \sin(\alpha + \beta) - \cos 2\alpha \cos(\alpha + \beta)) hhH \\
& +\frac{1}{4} \frac{g}{c_W} m_Z (2 \sin 2\alpha \cos(\alpha + \beta) + \cos 2\alpha \sin(\alpha + \beta)) hHH \\
& -\frac{1}{4} \frac{g}{c_W} m_Z \cos 2\beta \sin(\alpha + \beta) hAA + \frac{1}{4} \frac{g}{c_W} m_Z \cos 2\beta \cos(\alpha + \beta) HAA \\
& + \left(gm_W \sin(\alpha - \beta) - \frac{1}{2} \frac{g}{c_W} m_Z \cos 2\beta \sin(\alpha + \beta) \right) hH^+H^- \\
& + \left(-gm_W \cos(\alpha - \beta) + \frac{1}{2} \frac{g}{c_W} m_Z \cos 2\beta \cos(\alpha + \beta) \right) HH^+H^- \\
& = +C_{hhh} hhh + C_{HHH} HHH + C_{hhH} hhH + C_{hHH} hHH \\
& + C_{hAA} hAA + C_{HAA} HAA + C_{hH^+H^-} hH^+H^- + C_{HH^+H^-} HH^+H^-. \tag{52}
\end{aligned}$$

Couplings with gauginos, Higgsinos and Goldstinos

The sgoldstino (and neutral Higgs bosons) interactions with gauginos, Higgsinos and Goldstinos are

$$\begin{aligned}
\mathcal{L}_s \supset & (C_{s\psi_X\psi_X}) s_X \psi_X \psi_X + (C_{a\psi_X\psi_X}) i a_X \psi_X \psi_X \\
& + \left(C_{s\tilde{V}\tilde{V}}^K \right) s_X \tilde{V} \left(i \frac{\sigma^\mu}{2} \partial_\mu \right) \tilde{\bar{V}} + \left(C_{a\tilde{V}\tilde{V}}^K \right) i a_X \tilde{V} \left(i \frac{\sigma^\mu}{2} \partial_\mu \right) \tilde{\bar{V}} \\
& + \left(C_{h\psi_X\tilde{B}} \right) h \psi_X \tilde{B} + \left(C_{H\psi_X\tilde{B}} \right) H \psi_X \tilde{B} + \left(C_{h\psi_X\tilde{W}} \right) h \psi_X \tilde{W}^0 + \left(C_{H\psi_X\tilde{W}} \right) H \psi_X \tilde{W}^0 \\
& + \left(C_{h\Psi_X\tilde{H}_d^0} \right) h \Psi_X \tilde{H}_d^0 + \left(C_{h\Psi_X\tilde{H}_u^0} \right) h \Psi_X \tilde{H}_u^0 + \left(C_{H\Psi_X\tilde{H}_d^0} \right) H \Psi_X \tilde{H}_d^0 + \left(C_{H\Psi_X\tilde{H}_u^0} \right) H \Psi_X \tilde{H}_u^0 \\
& + \left(C_{A\Psi_X\tilde{H}_d^0} \right) i A \Psi_X \tilde{H}_d^0 + \left(C_{A\Psi_X\tilde{H}_u^0} \right) i A \Psi_X \tilde{H}_u^0 + \left(C_{s\tilde{H}_d^0\tilde{H}_u^0} \right) s_X \tilde{H}_d^0 \tilde{H}_u^0 + \left(C_{a\tilde{H}_d^0\tilde{H}_u^0} \right) i a_X \tilde{H}_d^0 \tilde{H}_u^0 \\
& + \left(C_{s\tilde{H}_u^+\tilde{H}_d^-} \right) s_X \tilde{H}_u^+ \tilde{H}_d^- + \left(C_{a\tilde{H}_u^+\tilde{H}_d^-} \right) i a_X \tilde{H}_u^+ \tilde{H}_d^- + \text{h.c.}, \tag{53}
\end{aligned}$$

$$\begin{aligned}
C_{s\psi_X\psi_X} &= -\frac{1}{2\sqrt{2}} \frac{m_X^2}{F} = -C_{a\psi_X\psi_X}, \quad C_{s\tilde{V}\tilde{V}}^K = \frac{\sqrt{2}M_a}{F} = C_{a\tilde{V}\tilde{V}}^K, \\
C_{h\psi_X\tilde{B}} &= s_W m_Z M_1 \sin(\alpha + \beta) / (2\sqrt{2}F), \quad C_{H\psi_X\tilde{B}} = -s_W m_Z M_1 \cos(\alpha + \beta) / (2\sqrt{2}F), \\
C_{h\psi_X\tilde{W}} &= -c_W m_Z M_2 \sin(\alpha + \beta) / (2\sqrt{2}F), \quad C_{H\psi_X\tilde{W}} = c_W m_Z M_2 \cos(\alpha + \beta) / (2\sqrt{2}F), \\
C_{h\Psi_X\tilde{H}_d^0} &= [2m_A^2 \cos(\alpha - \beta) \sin \beta - (2\mu^2 + m_Z^2 \cos 2\beta) \sin \alpha] / (2\sqrt{2}F), \\
C_{h\Psi_X\tilde{H}_u^0} &= [-2m_A^2 \cos(\alpha - \beta) \cos \beta + (2\mu^2 - m_Z^2 \cos 2\beta) \cos \alpha] / (2\sqrt{2}F), \\
C_{H\Psi_X\tilde{H}_d^0} &= [2m_A^2 \sin(\alpha - \beta) \sin \beta + (2\mu^2 + m_Z^2 \cos 2\beta) \cos \alpha] / (2\sqrt{2}F), \\
C_{H\Psi_X\tilde{H}_u^0} &= [-2m_A^2 \sin(\alpha - \beta) \cos \beta + (2\mu^2 - m_Z^2 \cos 2\beta) \sin \alpha] / (2\sqrt{2}F), \\
C_{A\Psi_X\tilde{H}_d^0} &= (2m_A^2 - 2\mu^2 - m_Z^2 \cos 2\beta) \sin \beta / (2\sqrt{2}F), \\
C_{A\Psi_X\tilde{H}_u^0} &= (2m_A^2 - 2\mu^2 + m_Z^2 \cos 2\beta) \cos \beta / (2\sqrt{2}F), \\
C_{s\tilde{H}_d^0\tilde{H}_u^0} &= C_{a\tilde{H}_d^0\tilde{H}_u^0} = m_A^2 \sin 2\beta / (2\sqrt{2}F), \\
C_{s\tilde{H}_u^+\tilde{H}_d^-} &= C_{a\tilde{H}_u^+\tilde{H}_d^-} = -m_A^2 \sin 2\beta / (2\sqrt{2}F), \tag{54}
\end{aligned}$$

where $(\tilde{V}\tilde{V})$ denotes $(\tilde{B}\tilde{B})$, $(\tilde{W}^0\tilde{W}^0)$, $(\tilde{W}^+\tilde{W}^-)$ and $(\lambda_g^a\lambda_g^a)$, and λ_g^a is the two-component gluino field.

Corresponding MSSM couplings are

$$\begin{aligned}
\mathcal{L} \supset & + \frac{g_{SW}}{2c_W} (-\sin \alpha h + \cos \alpha H - i \sin \beta A) \tilde{B} \tilde{H}_d^0 - \frac{g_{SW}}{2c_W} (\cos \alpha h + \sin \alpha H - i \cos \beta A) \tilde{B} \tilde{H}_u^0 \\
& - \frac{g}{2} (-\sin \alpha h + \cos \alpha H - i \sin \beta A) \tilde{W} \tilde{H}_d^0 + \frac{g}{2} (\cos \alpha h + \sin \alpha H - i \cos \beta A) \tilde{W} \tilde{H}_u^0 \\
& - \frac{g}{\sqrt{2}} (-\sin \alpha h + \cos \alpha H - i \sin \beta A) \tilde{W}^+ \tilde{H}_d^- \\
& - \frac{g}{\sqrt{2}} (\cos \alpha h + \sin \alpha H - i \cos \beta A) \tilde{H}_u^+ \tilde{W}^- + \text{h.c.} \\
= & \left(C_{h\tilde{B}\tilde{H}_d} h + C_{H\tilde{B}\tilde{H}_d} H + C_{A\tilde{B}\tilde{H}_d} iA \right) \tilde{B} \tilde{H}_d^0 + \left(C_{h\tilde{B}\tilde{H}_u} h + C_{H\tilde{B}\tilde{H}_u} H + C_{A\tilde{B}\tilde{H}_u} iA \right) \tilde{B} \tilde{H}_u^0 \\
& + \left(C_{h\tilde{W}\tilde{H}_d} h + C_{H\tilde{W}\tilde{H}_d} H + C_{A\tilde{W}\tilde{H}_d} iA \right) \tilde{W} \tilde{H}_d^0 + \left(C_{h\tilde{W}\tilde{H}_u} h + C_{H\tilde{W}\tilde{H}_u} H + C_{A\tilde{W}\tilde{H}_u} iA \right) \tilde{W} \tilde{H}_u^0 \\
& + \left(C_{h\tilde{W}^+\tilde{H}_d^-} h + C_{H\tilde{W}^+\tilde{H}_d^-} H + C_{A\tilde{W}^+\tilde{H}_d^-} iA \right) \tilde{W}^+ \tilde{H}_d^- \\
& + \left(C_{h\tilde{H}_u^+\tilde{W}^-} h + C_{H\tilde{H}_u^+\tilde{W}^-} H + C_{A\tilde{H}_u^+\tilde{W}^-} iA \right) \tilde{H}_u^+ \tilde{W}^- + \text{h.c.} \tag{55}
\end{aligned}$$

Couplings with fermion and sfermions

The mass matrices of sfermions are the same as in MSSM:

$$\begin{aligned}
V \supset & \left(\tilde{f}_L^* \tilde{f}_R^* \right) \begin{pmatrix} m_{\tilde{f}_{LL}}^2 & m_{\tilde{f}_{LR}}^2 \\ m_{\tilde{f}_{LR}}^{2*} & m_{\tilde{f}_{RR}}^2 \end{pmatrix} \begin{pmatrix} \tilde{f}_L \\ \tilde{f}_R \end{pmatrix}, \\
m_{\tilde{f}_{LL}}^2 = & m_{\tilde{f}_L}^2 + m_f^2 + m_Z^2 \cos 2\beta (T_{3L} - Qs_W^2) \\
m_{\tilde{f}_{RR}}^2 = & m_{\tilde{f}_R}^2 + m_f^2 + m_Z^2 \cos 2\beta (Qs_W^2) \\
m_{\tilde{f}_{LR}}^2 = & m_u(A_u/y_u + \mu/\tan \beta) \quad (\text{or}) \quad m_d(A_d/y_d + \mu \tan \beta), \tag{56}
\end{aligned}$$

where y_u, y_d are defined in Eq. (2). We define mass eigenbasis $\tilde{f}_i = (\tilde{f}_1, \tilde{f}_2)^T$ with $m_{\tilde{f}_1} < m_{\tilde{f}_2}$ by

$$\tilde{f}_i = U^f \tilde{f}' \tag{57}$$

where $\tilde{f}' = (\tilde{f}_L, \tilde{f}_R)$.

Sgoldstino interactions with sfermions are given by,

$$\begin{aligned}
\mathcal{L}_s \supset & [(C_{sff}) s_X f_L f_R^c + (C_{aff}) i a_X f_L f_R^c + \text{h.c.}] \\
& + (C_{s\tilde{t}_L\tilde{t}_L}) s_X \tilde{t}_L^* \tilde{t}_L + (C_{s\tilde{t}_R\tilde{t}_R}) s_X \tilde{t}_R^* \tilde{t}_R \\
& + [(C_{s\tilde{t}_L\tilde{t}_R}) s_X \tilde{t}_L^* \tilde{t}_R + (C_{a\tilde{t}_L\tilde{t}_R}) i a_X \tilde{t}_L^* \tilde{t}_R + \text{h.c.}] \tag{58}
\end{aligned}$$

$$\begin{aligned}
C_{stt} &= C_{att} = -\frac{1}{\sqrt{2}F} m_t \frac{A_t}{y_t}, \\
C_{s\tilde{t}_L\tilde{t}_L} &= -\frac{1}{F} \left[-\sqrt{2}m_t^2 \frac{A_t}{y_t} + \sqrt{2}m_Z^2 (s_W^2 M_1 + c_W^2 M_2) \cos 2\beta (T_3 - Qs_W^2) \right], \\
C_{s\tilde{t}_R\tilde{t}_R} &= -\frac{1}{F} \left[-\sqrt{2}m_t^2 \frac{A_t}{y_t} + \sqrt{2}m_Z^2 (s_W^2 M_1 + c_W^2 M_2) \cos 2\beta (Qs_W^2) \right], \\
C_{s\tilde{t}_L\tilde{t}_R} &= -\frac{1}{\sqrt{2}F} \frac{m_t}{\tan \beta} \left[A_t \mu + \frac{1}{2} m_A^2 \sin 2\beta \right] = -C_{a\tilde{t}_L\tilde{t}_R},
\end{aligned}$$

$$\begin{aligned}
C_{sbb} &= C_{abb} = -\frac{1}{\sqrt{2}F} m_b \frac{A_b}{y_b}, \\
C_{s\tilde{b}_L\tilde{b}_L} &= -\frac{1}{F} \left[-\sqrt{2}m_b^2 \frac{A_b}{y_b} + \sqrt{2}m_Z^2 (s_W^2 M_1 + c_W^2 M_2) \cos 2\beta (T_3 - Qs_W^2) \right], \\
C_{s\tilde{b}_R\tilde{b}_R} &= -\frac{1}{F} \left[-\sqrt{2}m_b^2 \frac{A_b}{y_b} + \sqrt{2}m_Z^2 (s_W^2 M_1 + c_W^2 M_2) \cos 2\beta (Qs_W^2) \right], \\
C_{s\tilde{b}_L\tilde{b}_R} &= -\frac{1}{\sqrt{2}F} m_b \tan \beta \left[A_b \mu + \frac{1}{2} m_A^2 \sin 2\beta \right] = -C_{a\tilde{b}_L\tilde{b}_R},
\end{aligned}$$

The MSSM interactions are

$$\begin{aligned}
\mathcal{L}_s &\supset [(C_{hff}) h f_L f_R^c + (C_{Hff}) H f_L f_R^c + (C_{Aff}) i A f_L f_R^c + \text{h.c.}] \\
&+ (C_{h\tilde{f}_L\tilde{f}_L}) h \tilde{f}_L^* \tilde{f}_L + (C_{H\tilde{f}_L\tilde{f}_L}) H \tilde{f}_L^* \tilde{f}_L + (C_{h\tilde{f}_R\tilde{f}_R}) h \tilde{f}_R^* \tilde{f}_R + (C_{H\tilde{f}_R\tilde{f}_R}) H \tilde{f}_R^* \tilde{f}_R \\
&+ [(C_{h\tilde{f}_L\tilde{f}_R}) h \tilde{f}_L^* \tilde{f}_R + (C_{H\tilde{f}_L\tilde{f}_R}) H \tilde{f}_L^* \tilde{f}_R + (C_{A\tilde{f}_L\tilde{f}_R}) i A \tilde{f}_L^* \tilde{f}_R + \text{h.c.}], \quad (59)
\end{aligned}$$

$$\begin{aligned}
C_{htt} &= -\frac{gm_t \cos \alpha}{2m_W \sin \beta}, \quad C_{Htt} = -\frac{gm_t \sin \alpha}{2m_W \sin \beta}, \quad C_{Att} = -\frac{gm_t}{2m_W \tan \beta}, \\
C_{h\tilde{t}_L\tilde{t}_L} &= \frac{gm_t^2 \cos \alpha}{m_W \sin \beta} - \frac{g}{c_W} m_Z \sin(\alpha + \beta) (T_3 - Qs_W^2), \\
C_{h\tilde{t}_R\tilde{t}_R} &= \frac{gm_t^2 \cos \alpha}{m_W \sin \beta} - \frac{g}{c_W} m_Z \sin(\alpha + \beta) (Qs_W^2), \\
C_{h\tilde{t}_L\tilde{t}_R} &= \frac{gm_t}{2m_W \sin \beta} (A_t/y_t \cos \alpha - \mu \sin \alpha), \\
C_{H\tilde{t}_L\tilde{t}_L} &= \frac{gm_t^2 \sin \alpha}{m_W \sin \beta} + \frac{g}{c_W} m_Z \cos(\alpha + \beta) (T_3 - Qs_W^2), \\
C_{H\tilde{t}_R\tilde{t}_R} &= \frac{gm_t^2 \sin \alpha}{m_W \sin \beta} + \frac{g}{c_W} m_Z \cos(\alpha + \beta) (Qs_W^2), \\
C_{H\tilde{t}_L\tilde{t}_R} &= \frac{gm_t}{2m_W \sin \beta} (A_t/y_t \sin \alpha + \mu \cos \alpha), \\
C_{A\tilde{t}_L\tilde{t}_R} &= -\frac{gm_t}{2m_W} (-(A_t/y_t)/\tan \beta + \mu),
\end{aligned}$$

$$\begin{aligned}
C_{hbb} &= \frac{gm_b \sin \alpha}{2m_W \cos \beta}, & C_{Hbb} &= -\frac{gm_b \cos \alpha}{2m_W \cos \beta}, & C_{Abb} &= -\frac{gm_b}{2m_W} \tan \beta, \\
C_{h\tilde{b}_L\tilde{b}_L} &= -\frac{gm_b^2 \sin \alpha}{m_W \cos \beta} - \frac{g}{c_W} m_Z \sin(\alpha + \beta) (T_3 - Qs_W^2), \\
C_{h\tilde{b}_R\tilde{b}_R} &= -\frac{gm_b^2 \sin \alpha}{m_W \cos \beta} - \frac{g}{c_W} m_Z \sin(\alpha + \beta) (Qs_W^2), \\
C_{h\tilde{b}_L\tilde{b}_R} &= \frac{gm_b}{2m_W \cos \beta} (-A_b/y_b \sin \alpha + \mu \cos \alpha), \\
C_{H\tilde{b}_L\tilde{b}_L} &= \frac{gm_b^2 \cos \alpha}{m_W \cos \beta} + \frac{g}{c_W} m_Z \cos(\alpha + \beta) (T_3 - Qs_W^2), \\
C_{H\tilde{b}_R\tilde{b}_R} &= \frac{gm_b^2 \cos \alpha}{m_W \cos \beta} + \frac{g}{c_W} m_Z \cos(\alpha + \beta) (Qs_W^2), \\
C_{H\tilde{b}_L\tilde{b}_R} &= \frac{gm_b}{2m_W \cos \beta} (A_b/y_b \cos \alpha + \mu \sin \alpha), \\
C_{A\tilde{b}_L\tilde{b}_R} &= -\frac{gm_b}{2m_W} (-(A_b/y_b) \tan \beta + \mu).
\end{aligned}$$

APPENDIX B: LAGRANGIAN

We now show the interaction terms written in the mass basis.

Couplings to gg , $\gamma\gamma$ and γZ

$$\begin{aligned}
\mathcal{L}_s^{\text{gauge1}} &= (C_{\phi_i gg}) \phi_i G^{\mu\nu} G_{\mu\nu} + (C_{\phi_i \gamma\gamma}) \phi_i F^{\mu\nu} F_{\mu\nu} + (C_{\phi_i \gamma Z}) \phi_i F^{\mu\nu} Z_{\mu\nu} \\
&\quad + (C_{\phi_{ai} gg}) a_i G^{\mu\nu} \tilde{G}_{\mu\nu} + (C_{\phi_{ai} \gamma\gamma}) a_i F^{\mu\nu} \tilde{F}_{\mu\nu} + (C_{\phi_{ai} \gamma Z}) a_i F^{\mu\nu} \tilde{Z}_{\mu\nu},
\end{aligned} \tag{60}$$

where

$$\begin{aligned}
C_{\phi_i gg} &= \sum_j S_{ij} C_{h_j gg}, & C_{\phi_{ai} gg} &= \sum_j A_{ij} C_{A_j gg}, \\
C_{\phi_i \gamma\gamma} &= \sum_j S_{ij} C_{h_j \gamma\gamma}, & C_{\phi_{ai} \gamma\gamma} &= \sum_j A_{ij} C_{A_j \gamma\gamma}, \\
C_{\phi_i \gamma Z} &= \sum_j S_{ij} C_{h_j \gamma Z}, & C_{\phi_{ai} \gamma Z} &= \sum_j A_{ij} C_{A_j \gamma Z}.
\end{aligned}$$

Couplings to WW and ZZ

$$\begin{aligned}
\mathcal{L}_s^{\text{gauge}^2} = & (C_{\phi_i WW_T}) \phi_i W^{\mu\nu} W_{\mu\nu} + (C_{\phi_i WW_L}) m_W^2 \phi_i W^\mu W_\mu \\
& + (C_{\phi_i ZZ_T}) \phi_i Z^{\mu\nu} Z_{\mu\nu} + (C_{\phi_i ZZ_L}) m_Z^2 \phi_i Z^\mu Z_\mu \\
& + (C_{\phi_{ai} WW_T}) \phi_{ai} W^{\mu\nu} \tilde{W}_{\mu\nu} + (C_{\phi_{ai} ZZ_T}) \phi_{ai} Z^{\mu\nu} \tilde{Z}_{\mu\nu},
\end{aligned} \tag{61}$$

where

$$\begin{aligned}
C_{\phi_i WW_T} &= \sum_j S_{ij} C_{h_j WW_T}, & C_{\phi_{ai} WW_T} &= \sum_j A_{ij} C_{A_j WW_T}, \\
C_{\phi_i ZZ_T} &= \sum_j S_{ij} C_{h_j ZZ_T}, & C_{\phi_{ai} ZZ_T} &= \sum_j A_{ij} C_{A_j ZZ_T}, \\
C_{\phi_i WW_L} &= \sum_j S_{ij} C_{h_j WW_L}, \\
C_{\phi_i ZZ_L} &= \sum_j S_{ij} C_{h_j ZZ_L}.
\end{aligned}$$

Couplings to Higgs bosons

$$\mathcal{L}_s^{\text{scalar}} = (C_{\phi_i \phi_j \phi_k}) \phi_i \phi_j \phi_k + (C_{\phi_i \phi_{aj} \phi_{ak}}) \phi_i a_j a_k + (C_{\phi_i H^+ H^-}) \phi_i H^+ H^-, \tag{62}$$

where

$$\begin{aligned}
C_{\phi_i \phi_j \phi_k} &= \sum_{i'j'k'} S_{ii'} S_{jj'} S_{kk'} C_{h_{i'} h_{j'} h_{k'}}, \\
C_{\phi_i \phi_{aj} \phi_{ak}} &= \sum_{i'j'k'} S_{ii'} A_{jj'} A_{kk'} C_{h_{i'} A_{j'} A_{k'}}, \\
C_{\phi_i H^+ H^-} &= \sum_j S_{ij} C_{h_j H^+ H^-}.
\end{aligned}$$

Couplings to Neutralinos and Goldstinos

$$\begin{aligned}
\mathcal{L}_s^{\text{neutralino}} = & \phi_i \bar{\psi}_{\tilde{\chi}_j} \left[\left(C_{\phi_i \psi_{\tilde{\chi}_j} \psi_{\tilde{\chi}_k}}^S \right) + \left(C_{\phi_i \psi_{\tilde{\chi}_j} \psi_{\tilde{\chi}_k}}^P \right) i\gamma_5 + \left(C_{\phi_i \psi_{\tilde{\chi}_j} \psi_{\tilde{\chi}_k}}^{KS} \right) i\frac{\not{\partial}}{2} + \left(C_{\phi_i \psi_{\tilde{\chi}_j} \psi_{\tilde{\chi}_k}}^{KP} \right) \frac{\not{\partial}}{2} \gamma_5 \right] \psi_{\tilde{\chi}_k} \\
& + a_i \bar{\psi}_{\tilde{\chi}_j} \left[\left(C_{\phi_{ai} \psi_{\tilde{\chi}_j} \psi_{\tilde{\chi}_k}}^S \right) + \left(C_{\phi_{ai} \psi_{\tilde{\chi}_j} \psi_{\tilde{\chi}_k}}^P \right) i\gamma_5 + \frac{1}{2} \overleftrightarrow{\not{\partial}} \gamma_5 + \left(C_{\phi_{ai} \psi_{\tilde{\chi}_j} \psi_{\tilde{\chi}_k}}^{KS} \right) i\frac{\not{\partial}}{2} + \left(C_{\phi_{ai} \psi_{\tilde{\chi}_j} \psi_{\tilde{\chi}_k}}^{KP} \right) \frac{\not{\partial}}{2} \gamma_5 \right] \psi_{\tilde{\chi}_k},
\end{aligned} \tag{63}$$

where

$$\begin{aligned}
C_{\phi_i \psi_{\tilde{\chi}_j} \psi_{\tilde{\chi}_k}}^S &= \sum_{i'j'k'} S_{ii'} N'_{jj'} N'_{kk'} C_{h_{i'} \tilde{N}_{j'}^0 \tilde{N}_{k'}^0} \text{Re}(\xi_j \xi_k), \\
C_{\phi_i \psi_{\tilde{\chi}_j} \psi_{\tilde{\chi}_k}}^P &= \sum_{i'j'k'} S_{ii'} N'_{jj'} N'_{kk'} C_{h_{i'} \tilde{N}_{j'}^0 \tilde{N}_{k'}^0} \{-\text{Im}(\xi_j \xi_k)\}, \\
C_{\phi_i \psi_{\tilde{\chi}_j} \psi_{\tilde{\chi}_k}}^{KS} &= \sum_{i'j'k'} S_{ii'} N'_{jj'} N'_{kk'} C_{h_{i'} \tilde{N}_{j'}^0 \tilde{N}_{k'}^0} \text{Re}(\xi_j^* \xi_k), \\
C_{\phi_i \psi_{\tilde{\chi}_j} \psi_{\tilde{\chi}_k}}^{KP} &= \sum_{i'j'k'} S_{ii'} N'_{jj'} N'_{kk'} C_{h_{i'} \tilde{N}_{j'}^0 \tilde{N}_{k'}^0} \text{Im}(\xi_j^* \xi_k), \\
C_{\phi_{ai} \psi_{\tilde{\chi}_j} \psi_{\tilde{\chi}_k}}^S &= \sum_{i'j'k'} A_{ii'} N'_{jj'} N'_{kk'} C_{A_{i'} \tilde{N}_{j'}^0 \tilde{N}_{k'}^0} \{-\text{Im}(\xi_j \xi_k)\}, \\
C_{\phi_{ai} \psi_{\tilde{\chi}_j} \psi_{\tilde{\chi}_k}}^P &= \sum_{i'j'k'} A_{ii'} N'_{jj'} N'_{kk'} C_{A_{i'} \tilde{N}_{j'}^0 \tilde{N}_{k'}^0} \{-\text{Re}(\xi_j \xi_k)\}, \\
C_{\phi_{ai} \psi_{\tilde{\chi}_j} \psi_{\tilde{\chi}_k}}^{KS} &= \sum_{i'j'k'} A_{ii'} N'_{jj'} N'_{kk'} C_{A_{i'} \tilde{N}_{j'}^0 \tilde{N}_{k'}^0} \text{Im}(\xi_j^* \xi_k), \\
C_{\phi_{ai} \psi_{\tilde{\chi}_j} \psi_{\tilde{\chi}_k}}^{KP} &= \sum_{i'j'k'} A_{ii'} N'_{jj'} N'_{kk'} C_{A_{i'} \tilde{N}_{j'}^0 \tilde{N}_{k'}^0} \{-\text{Re}(\xi_j^* \xi_k)\}.
\end{aligned}$$

Couplings to Charginos

$$\begin{aligned}
\mathcal{L}_s^{\text{chargino}} &= \phi_i \bar{\psi}_{\tilde{\chi}_j^+} \left[\left(C_{\phi_i \psi_{\tilde{\chi}_j^+} \psi_{\tilde{\chi}_k^-}}^S \right) + \left(C_{\phi_i \psi_{\tilde{\chi}_j^+} \psi_{\tilde{\chi}_k^-}}^P \right) \gamma_5 \right. \\
&\quad \left. + \left(C_{\phi_i \psi_{\tilde{\chi}_j^+} \psi_{\tilde{\chi}_k^-}}^{KS} \right) i \frac{\vec{\not{\partial}} - \overleftarrow{\not{\partial}}}{2} + \left(C_{\phi_i \psi_{\tilde{\chi}_j^+} \psi_{\tilde{\chi}_k^-}}^{KP} \right) i \frac{\vec{\not{\partial}} - \overleftarrow{\not{\partial}}}{2} \gamma_5 \right] \psi_{\tilde{\chi}_k^-} \\
&+ a_i \bar{\psi}_{\tilde{\chi}_j^+} \left[\left(C_{a_i \psi_{\tilde{\chi}_j^+} \psi_{\tilde{\chi}_k^-}}^S \right) i + \left(C_{a_i \psi_{\tilde{\chi}_j^+} \psi_{\tilde{\chi}_k^-}}^P \right) i \gamma_5 \right. \\
&\quad \left. + \left(C_{a_i \psi_{\tilde{\chi}_j^+} \psi_{\tilde{\chi}_k^-}}^{KS} \right) \frac{\vec{\not{\partial}} + \overleftarrow{\not{\partial}}}{2} + \left(C_{a_i \psi_{\tilde{\chi}_j^+} \psi_{\tilde{\chi}_k^-}}^{KP} \right) \frac{\vec{\not{\partial}} + \overleftarrow{\not{\partial}}}{2} \gamma_5 \right] \psi_{\tilde{\chi}_k^-},
\end{aligned} \tag{64}$$

where

$$\begin{aligned}
C_{\phi_i \psi_{\tilde{\chi}_j}^+ \psi_{\tilde{\chi}_k}^-}^S &= \sum_{i'j'k'} \frac{1}{2} S_{ii'} (C_{jj'}^R C_{kk'}^L + C_{kj'}^R C_{jk'}^L) C_{h_{i'}} \tilde{C}_{j'}^+ \tilde{C}_{k'}^-, \\
C_{\phi_i \psi_{\tilde{\chi}_j}^+ \psi_{\tilde{\chi}_k}^-}^P &= \sum_{i'j'k'} \frac{1}{2} S_{ii'} (C_{jj'}^R C_{kk'}^L - C_{kj'}^R C_{jk'}^L) C_{h_{i'}} \tilde{C}_{j'}^+ \tilde{C}_{k'}^-, \\
C_{\phi_i \psi_{\tilde{\chi}_j}^+ \psi_{\tilde{\chi}_k}^-}^{KS} &= \sum_{i'j'k'} \frac{1}{2} S_{ii'} (C_{jj'}^R C_{kk'}^R + C_{jj'}^L C_{kk'}^L) C_{h_{i'}} \tilde{C}_{j'}^+ \tilde{C}_{k'}^-, \\
C_{\phi_i \psi_{\tilde{\chi}_j}^+ \psi_{\tilde{\chi}_k}^-}^{KP} &= \sum_{i'j'k'} \frac{1}{2} S_{ii'} (C_{jj'}^R C_{kk'}^R - C_{jj'}^L C_{kk'}^L) C_{h_{i'}} \tilde{C}_{j'}^+ \tilde{C}_{k'}^-, \\
C_{a_i \psi_{\tilde{\chi}_j}^+ \psi_{\tilde{\chi}_k}^-}^S &= \sum_{i'j'k'} \frac{1}{2} S_{ii'} (-C_{jj'}^R C_{kk'}^L + C_{kj'}^R C_{jk'}^L) C_{A_{i'}} \tilde{C}_{j'}^+ \tilde{C}_{k'}^-, \\
C_{a_i \psi_{\tilde{\chi}_j}^+ \psi_{\tilde{\chi}_k}^-}^P &= \sum_{i'j'k'} \frac{1}{2} S_{ii'} (-C_{jj'}^R C_{kk'}^L - C_{kj'}^R C_{jk'}^L) C_{A_{i'}} \tilde{C}_{j'}^+ \tilde{C}_{k'}^-, \\
C_{a_i \psi_{\tilde{\chi}_j}^+ \psi_{\tilde{\chi}_k}^-}^{KS} &= \sum_{i'j'k'} \frac{1}{2} S_{ii'} (-C_{jj'}^R C_{kk'}^R + C_{jj'}^L C_{kk'}^L) C_{A_{i'}} \tilde{C}_{j'}^+ \tilde{C}_{k'}^-, \\
C_{a_i \psi_{\tilde{\chi}_j}^+ \psi_{\tilde{\chi}_k}^-}^{KP} &= \sum_{i'j'k'} \frac{1}{2} S_{ii'} (-C_{jj'}^R C_{kk'}^R - C_{jj'}^L C_{kk'}^L) C_{A_{i'}} \tilde{C}_{j'}^+ \tilde{C}_{k'}^-.
\end{aligned}$$

Couplings to Gluino

$$\mathcal{L}_s^{\text{ino}} = (C_{\phi_i \tilde{g} \tilde{g}}^K) \phi_i \bar{\psi}_g^a \left(i \frac{\not{\partial}}{2} \right) \psi_g^a + (C_{\phi_{ai} \tilde{g} \tilde{g}}^K) a_i \bar{\psi}_g^a \left(\frac{\not{\partial}}{2} \gamma_5 \right) \psi_g^a, \quad (65)$$

where

$$C_{\phi_i \tilde{g} \tilde{g}}^K = \sum_j S_{ij} C_{h_j \tilde{g} \tilde{g}}^K, \quad C_{\phi_{ai} \tilde{g} \tilde{g}}^K = \sum_j A_{ij} C_{A_j \tilde{g} \tilde{g}}^K \{-1\}.$$

Couplings to fermion and sfermions

$$\mathcal{L}_s \supset + (C_{\phi_i \tilde{f}_j \tilde{f}_k}) \phi_i \tilde{f}_j^* \tilde{f}_k + (C_{\phi_{ai} \tilde{f}_j \tilde{f}_k}) i a_i \tilde{f}_j^* \tilde{f}_k + (C_{\phi_i f f}) \phi_i \bar{\psi}_f \psi_f + (C_{\phi_{ai} f f}) i a_i \bar{\psi}_f \gamma_5 \psi_f, \quad (66)$$

where

$$\begin{aligned}
C_{\phi_i \tilde{f} \tilde{f}} &= \sum_{i' j' k'} S_{ii'} U_{jj'}^{f*} U_{kk'}^f C_{h_{i'} \tilde{f}_{j'} \tilde{f}_{k'}}, & C_{\phi_{ai} \tilde{f} \tilde{f}} &= \sum_{i' j' k'} A_{ii'} U_{jj'}^{f*} U_{kk'}^f C_{A_{i'} \tilde{f}_{j'} \tilde{f}_{k'}}, \\
C_{\phi_i f f} &= \sum_j S_{ij} C_{h_j f f}, & C_{\phi_{ai} f f} &= - \sum_j A_{ij} C_{A_j f f}.
\end{aligned}$$

APPENDIX C: DECAY WIDTH

From the effective Lagrangian presented in Appendix B, the decay widths of ϕ_i , which includes the sgoldstino, into SM gauge bosons and gravitino \tilde{G} are obtained as

$$\begin{aligned}
\Gamma(\phi_i \rightarrow gg) &= \frac{2}{\pi} C_{\phi_i gg}^2 m_{\phi_i}^3, \\
\Gamma(\phi_i \rightarrow \gamma\gamma) &= \frac{1}{4\pi} C_{\phi_i \gamma\gamma}^2 m_{\phi_i}^3, \\
\Gamma(\phi_i \rightarrow \gamma Z) &= \frac{1}{8\pi} C_{\phi_i \gamma Z}^2 m_{\phi_i}^3 \left(1 - \frac{m_Z^2}{m_{\phi_i}^2}\right)^3, \\
\Gamma(\phi_i \rightarrow WW) &= \frac{1}{16\pi} \frac{m_W^4}{m_{\phi_i}} \left[2C_{\phi_i WW_T}^2 \left(6 - 4\frac{m_{\phi_i}^2}{m_W^2} + \frac{m_{\phi_i}^4}{m_W^4}\right) - 12C_{\phi_i WW_T} C_{\phi_i WW_L} \left(1 - \frac{m_{\phi_i}^2}{2m_W^2}\right) \right. \\
&\quad \left. + C_{\phi_i WW_L}^2 \left(3 - \frac{m_{\phi_i}^2}{m_W^2} + \frac{1}{4} \frac{m_{\phi_i}^4}{m_W^4}\right) \right] \sqrt{1 - \frac{4m_W^2}{m_{\phi_i}^2}}, \\
\Gamma(\phi_i \rightarrow ZZ) &= \frac{1}{8\pi} \frac{m_Z^4}{m_{\phi_i}} \left[2C_{\phi_i ZZ_T}^2 \left(6 - 4\frac{m_{\phi_i}^2}{m_Z^2} + \frac{m_{\phi_i}^4}{m_Z^4}\right) - 12C_{\phi_i ZZ_T} C_{\phi_i ZZ_L} \left(1 - \frac{m_{\phi_i}^2}{2m_Z^2}\right) \right. \\
&\quad \left. + C_{\phi_i ZZ_L}^2 \left(3 - \frac{m_{\phi_i}^2}{m_Z^2} + \frac{1}{4} \frac{m_{\phi_i}^4}{m_Z^4}\right) \right] \sqrt{1 - \frac{4m_Z^2}{m_{\phi_i}^2}}, \\
\Gamma(\phi_i \rightarrow ff) &= \frac{C^{\text{color}}}{8\pi} C_{\phi_i ff}^2 m_{\phi_i} \left(1 - \frac{4m_f^2}{m_{\phi_i}^2}\right)^{3/2}, \\
\Gamma(\phi_i \rightarrow \tilde{G}\tilde{G}) &\approx \frac{1}{4\pi} C_{\phi_i \psi_X \psi_X}^2 m_{\phi_i}, \tag{67}
\end{aligned}$$

where C^{color} is 3 (1) for squark (slepton). The partial width for decay to scalars is given by

$$\begin{aligned}
\Gamma(\phi_i \rightarrow \phi_j \phi_j) &= \frac{1}{8\pi} \tilde{C}_{\phi_i \phi_j \phi_j}^2 \frac{1}{m_{\phi_i}} \sqrt{1 - \frac{4m_{\phi_j}^2}{m_{\phi_i}^2}}, \\
\Gamma(\phi_3 \rightarrow \phi_1 \phi_2) &= \frac{1}{16\pi} \tilde{C}_{\phi_3 \phi_1 \phi_2}^2 \frac{1}{m_{\phi_3}} \sqrt{1 - 2\frac{m_{\phi_1}^2 + m_{\phi_2}^2}{m_{\phi_3}^2} + \frac{(m_{\phi_1}^2 - m_{\phi_2}^2)^2}{m_{\phi_3}^4}}, \tag{68}
\end{aligned}$$

where $\tilde{C}_{\phi_i \phi_j \phi_j} = C_{\phi_i \phi_j \phi_j} + C_{\phi_j \phi_i \phi_j} + C_{\phi_j \phi_j \phi_i}$ and $\tilde{C}_{\phi_3 \phi_1 \phi_2} = C_{\phi_1 \phi_2 \phi_3} + C_{\phi_1 \phi_3 \phi_2} + C_{\phi_2 \phi_1 \phi_3} + C_{\phi_2 \phi_3 \phi_1} + C_{\phi_3 \phi_1 \phi_2} + C_{\phi_3 \phi_2 \phi_1}$. We can write the partial width for sgoldstino decays to several

SUSY particle final states as

$$\begin{aligned}
\Gamma(\phi_i \rightarrow \psi_{\tilde{\chi}_j} \psi_{\tilde{\chi}_k}) &= C_{jk}^{\text{sym}} \frac{1}{8\pi} m_{\phi_i} \sqrt{1 - 2 \frac{m_j^2 + m_k^2}{m_{\phi_i}^2} + \frac{(m_j^2 - m_k^2)^2}{m_{\phi_i}^4}} \\
&\times \left[\left(C_{\phi_i \psi_{\tilde{\chi}_j} \psi_{\tilde{\chi}_k}}^S + C_{\phi_i \psi_{\tilde{\chi}_k} \psi_{\tilde{\chi}_j}}^S + C_{\phi_i \psi_{\tilde{\chi}_j} \psi_{\tilde{\chi}_k}}^{KS} \frac{m_j + m_k}{2} \right)^2 \left\{ 1 - \left(\frac{m_j + m_k}{m_{\phi_i}} \right)^2 \right\} \right. \\
&\quad \left. + \left(C_{\phi_i \psi_{\tilde{\chi}_j} \psi_{\tilde{\chi}_k}}^P + C_{\phi_i \psi_{\tilde{\chi}_k} \psi_{\tilde{\chi}_j}}^P + C_{\phi_i \psi_{\tilde{\chi}_j} \psi_{\tilde{\chi}_k}}^{KP} \frac{m_k - m_j}{2} \right)^2 \left\{ 1 - \left(\frac{m_j - m_k}{m_{\phi_i}} \right)^2 \right\} \right], \\
\Gamma(\phi_i \rightarrow \psi_{\tilde{\chi}_j}^+ \psi_{\tilde{\chi}_k}^-) &= \frac{1}{8\pi} m_{\phi_i} \sqrt{1 - 2 \frac{m_j^2 + m_k^2}{m_{\phi_i}^2} + \frac{(m_j^2 - m_k^2)^2}{m_{\phi_i}^4}} \\
&\times \left[\left(C_{\phi_i \psi_{\tilde{\chi}_j}^+ \psi_{\tilde{\chi}_k}^-}^S + C_{\phi_i \psi_{\tilde{\chi}_j}^+ \psi_{\tilde{\chi}_k}^-}^{KS} \frac{m_j + m_k}{2} \right)^2 \left\{ 1 - \left(\frac{m_j + m_k}{m_{\phi_i}} \right)^2 \right\} \right. \\
&\quad \left. + \left(C_{\phi_i \psi_{\tilde{\chi}_j}^+ \psi_{\tilde{\chi}_k}^-}^P + C_{\phi_i \psi_{\tilde{\chi}_j}^+ \psi_{\tilde{\chi}_k}^-}^{KP} \frac{m_j - m_k}{2} \right)^2 \left\{ 1 - \left(\frac{m_j - m_k}{m_{\phi_i}} \right)^2 \right\} \right], \\
\Gamma(\phi_i \rightarrow \tilde{f}_1^* \tilde{f}_1) &= \frac{C^{\text{color}}}{16\pi} C_{\phi_i \tilde{f}_1 \tilde{f}_1}^2 \frac{1}{m_{\phi_i}} \sqrt{1 - \frac{4m_{\tilde{f}_1}^2}{m_{\phi_i}^2}}, \\
\Gamma(\phi_i \rightarrow \tilde{f}_1^* \tilde{f}_2) &= \frac{C^{\text{color}}}{16\pi} C_{\phi_i \tilde{f}_1 \tilde{f}_2}^2 \frac{1}{m_{\phi_i}} \sqrt{1 - 2 \frac{m_{\tilde{f}_1}^2 + m_{\tilde{f}_2}^2}{m_{\phi_i}^2} + \frac{(m_{\tilde{f}_1}^2 - m_{\tilde{f}_2}^2)^2}{m_{\phi_i}^4}}, \\
\Gamma(\phi_i \rightarrow \tilde{f}_1 \tilde{f}_2^*) &= \Gamma(\phi_i \rightarrow \tilde{f}_1^* \tilde{f}_2), \tag{69}
\end{aligned}$$

where $C_{jk}^{\text{sym}} = 1/2$ (1) if $j = k$ ($j \neq k$). C^{color} is 3 (1) for squark (slepton).

The pseudo-sgoldsino decay widths are

$$\begin{aligned}
\Gamma(a_i \rightarrow gg) &= \frac{2}{\pi} C_{a_i gg}^2 m_{a_i}^3, \\
\Gamma(a_i \rightarrow \gamma\gamma) &= \frac{1}{4\pi} C_{a_i \gamma\gamma}^2 m_{a_i}^3, \\
\Gamma(a_i \rightarrow \gamma Z) &= \frac{1}{8\pi} C_{a_i \gamma Z}^2 m_{a_i}^3 \left(1 - \frac{m_Z^2}{m_{a_i}^2} \right)^3, \\
\Gamma(a_i \rightarrow WW) &= \frac{1}{8\pi} C_{a_i WW}^2 m_{a_i}^3 \left(1 - \frac{4m_W^2}{m_{a_i}^2} \right)^{5/2}, \\
\Gamma(a_i \rightarrow ZZ) &= \frac{1}{4\pi} C_{a_i ZZ}^2 m_{a_i}^3 \left(1 - \frac{4m_Z^2}{m_{a_i}^2} \right)^{5/2}, \tag{70}
\end{aligned}$$

$$\begin{aligned}
\Gamma(a_i \rightarrow ff) &= \frac{C^{\text{color}}}{8\pi} C_{a_i f f}^2 m_{a_i} \sqrt{1 - \frac{4m_f^2}{m_{a_i}^2}}, \\
\Gamma(a_i \rightarrow \tilde{G}\tilde{G}) &\approx \frac{1}{4\pi} C_{a_i \psi_X \psi_X}^2 m_{\phi_i}, \\
\Gamma(a_2 \rightarrow a_1 \phi_i) &= \frac{1}{16\pi} \tilde{C}_{\phi_i a_1 a_2}^2 \frac{1}{m_{a_2}} \sqrt{1 - 2 \frac{m_{a_1}^2 + m_{\phi_i}^2}{m_{a_2}^2} + \frac{(m_{a_1}^2 - m_{\phi_i}^2)^2}{m_{a_2}^4}}, \\
\Gamma(a_i \rightarrow \psi_{\tilde{\chi}_j} \psi_{\tilde{\chi}_k}) &= C_{jk}^{\text{sym}} \frac{1}{8\pi} m_{a_i} \sqrt{1 - 2 \frac{m_j^2 + m_k^2}{m_{a_i}^2} + \frac{(m_j^2 - m_k^2)^2}{m_{a_i}^4}} \\
&\quad \times \left[\left(C_{a_i \psi_{\tilde{\chi}_j} \psi_{\tilde{\chi}_k}}^S + C_{a_i \psi_{\tilde{\chi}_k} \psi_{\tilde{\chi}_j}}^S + C_{a_i \psi_{\tilde{\chi}_j} \psi_{\tilde{\chi}_k}}^{KS} \frac{m_k - m_j}{2} \right)^2 \left\{ 1 - \left(\frac{m_j + m_k}{m_{a_i}} \right)^2 \right\} \right. \\
&\quad \left. + \left(C_{a_i \psi_{\tilde{\chi}_j} \psi_{\tilde{\chi}_k}}^P + C_{a_i \psi_{\tilde{\chi}_k} \psi_{\tilde{\chi}_j}}^P + C_{a_i \psi_{\tilde{\chi}_j} \psi_{\tilde{\chi}_k}}^{KP} \frac{m_j + m_k}{2} \right)^2 \left\{ 1 - \left(\frac{m_j - m_k}{m_{a_i}} \right)^2 \right\} \right], \\
\Gamma(a_i \rightarrow \psi_{\tilde{\chi}_j}^+ \psi_{\tilde{\chi}_k}^-) &= \frac{1}{8\pi} m_{a_i} \sqrt{1 - 2 \frac{m_j^2 + m_k^2}{m_{a_i}^2} + \frac{(m_j^2 - m_k^2)^2}{m_{a_i}^4}} \\
&\quad \times \left[\left(C_{a_i \psi_{\tilde{\chi}_j}^+ \psi_{\tilde{\chi}_k}^-}^S + C_{a_i \psi_{\tilde{\chi}_j}^+ \psi_{\tilde{\chi}_k}^-}^{KS} \frac{m_j - m_k}{2} \right)^2 \left\{ 1 - \left(\frac{m_j + m_k}{m_{a_i}} \right)^2 \right\} \right. \\
&\quad \left. + \left(C_{a_i \psi_{\tilde{\chi}_j}^+ \psi_{\tilde{\chi}_k}^-}^P + C_{a_i \psi_{\tilde{\chi}_j}^+ \psi_{\tilde{\chi}_k}^-}^{KP} \frac{m_j + m_k}{2} \right)^2 \left\{ 1 - \left(\frac{m_j - m_k}{m_{a_i}} \right)^2 \right\} \right], \\
\Gamma(a_i \rightarrow \tilde{f}_1^* \tilde{f}_2) &= \frac{C^{\text{color}}}{16\pi} C_{a_i \tilde{f}_1 \tilde{f}_2}^2 \frac{1}{m_{a_i}} \sqrt{1 - 2 \frac{m_{\tilde{f}_1}^2 + m_{\tilde{f}_2}^2}{m_{a_i}^2} + \frac{(m_{\tilde{f}_1}^2 - m_{\tilde{f}_2}^2)^2}{m_{a_i}^4}}, \\
\Gamma(a_i \rightarrow \tilde{f}_1 \tilde{f}_2^*) &= \Gamma(a_i \rightarrow \tilde{f}_1^* \tilde{f}_2), \tag{71}
\end{aligned}$$

where $\tilde{C}_{\phi_i a_1 a_2} = C_{\phi_i a_1 a_2} + C_{\phi_i a_2 a_1}$.

APPENDIX D: HIGGS POTENTIAL UP TO $O(1/F^2)$

In this Appendix, we suppose the following lagrangian,

$$\begin{aligned}
\mathcal{L}_K &= \int d\theta^4 \left[\left(1 - \frac{m_{\tilde{f}_i}^2}{F^2} X^\dagger X \right) \Phi_i^\dagger e^V \Phi_i + \left(1 - \frac{m_{H_{u,d}}^2}{F^2} X^\dagger X \right) H_{u,d}^\dagger e^V H_{u,d} \right. \\
&\quad \left. + \left\{ - \left(\frac{\mu_k}{F} X^\dagger + \frac{B_{\mu k}}{F^2} X^\dagger X \right) H_d \cdot H_u + h.c. \right\} \right], \tag{72} \\
\mathcal{L}_W &= \int d\theta^2 \left[\frac{1}{4} \left(1 + \frac{2M_a}{F} X \right) \text{Tr}[W^{a\alpha} W_\alpha^a] + \left(\mu_w + \frac{B_{\mu w}}{F} X \right) H_d \cdot H_u + \frac{A_X}{F} X X H_d \cdot H_u \right. \\
&\quad \left. + \left(y_e + \frac{A_e}{F} X \right) H_d \cdot L E^c + \left(y_d + \frac{A_d}{F} X \right) H_d \cdot Q D^c + \left(y_u + \frac{A_u}{F} X \right) H_u \cdot Q U^c \right] + h.c..
\end{aligned}$$

The D- and F-term contributions, V_D and V_F to the Higgs-goldstino potential are written as

$$V_D = \frac{g'^2}{8} \left(1 + \frac{2M_1}{F} \frac{\phi_X + \phi_X^*}{2} \right)^{-1} \left\{ \left(1 - \frac{m_{H_u}^2}{F^2} |\phi_X|^2 \right) |H_u|^2 - \left(1 - \frac{m_{H_d}^2}{F^2} |\phi_X|^2 \right) |H_d|^2 \right\}^2 \quad (73)$$

$$+ \frac{g_2^2}{8} \left(1 + \frac{2M_2}{F} \frac{\phi_X + \phi_X^*}{2} \right)^{-1} \left\{ \left(1 - \frac{m_{H_u}^2}{F^2} |\phi_X|^2 \right) H_u^\dagger \sigma^i H_u + \left(1 - \frac{m_{H_d}^2}{F^2} |\phi_X|^2 \right) H_d^\dagger \sigma^i H_d \right\}^2,$$

$$V_F = \left(1 - \frac{m_{H_u}^2}{F^2} |\phi_X|^2 \right)^{-1} \left| - \left(\mu_{\text{eff}} + \frac{B_{\mu\text{eff}}}{F} \phi_X - \frac{A_X}{F} \phi_X^2 \right) \epsilon_{ij} H_d^i + \frac{m_{H_u}^2}{F} \phi_X H_u^{*j} - (O_{1/F^2}) \mu_k \epsilon_{ij} H_d^i \right|^2$$

$$+ \left(1 - \frac{m_{H_d}^2}{F^2} |\phi_X|^2 \right)^{-1} \left| - \left(\mu_{\text{eff}} + \frac{B_{\mu\text{eff}}}{F} \phi_X - \frac{A_X}{F} \phi_X^2 \right) \epsilon_{ij} H_u^j + \frac{m_{H_d}^2}{F} \phi_X H_d^{*i} - (O_{1/F^2}) \mu_k \epsilon_{ij} H_u^j \right|^2$$

$$+ \left[1 - \frac{m_X^2}{F^2} |\phi_X|^2 - \frac{m_{H_u}^2}{F^2} |H_u|^2 - \frac{m_{H_d}^2}{F^2} |H_d|^2 - \frac{B_{\mu k}}{F^2} \left\{ H_d \cdot H_u + (H_d \cdot H_u)^\dagger \right\} \right]^{-1}$$

$$\times \left| -F - 2 \frac{A_X}{F} \phi_X H_d \cdot H_u - \frac{B_{\mu w}}{F} H_d \cdot H_u \right|^2, \quad (74)$$

$$O_{1/F^2} = \frac{m_X^2}{F^2} |\phi_X|^2 + \frac{\mu_w \mu_k + \mu_k^2 + m_{H_u}^2}{F^2} |H_u|^2 + \frac{\mu_w \mu_k + \mu_k^2 + m_{H_d}^2}{F^2} |H_d|^2$$

$$- \frac{-2A_X \phi_X - B_{\mu w} - B_{\mu k}}{F^2} H_d \cdot H_u + \frac{B_{\mu k}}{F^2} (H_d \cdot H_u)^\dagger, \quad (75)$$

respectively. Here, $\mu_{\text{eff}} = \mu_w + \mu_k$ and $B_{\mu\text{eff}} = B_{\mu w} + B_{\mu k}$.

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